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Preliminary Design

Configuration and Design Study of Manipulator Systems Applicable to the Freeflying Teleoperator

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PRELIMINARY DESIGN

CONFIGURATION AND DESIGN STUDY OF MANIPULATOR SYSTEMS APPLICABLE TO THE FREE-FLYING TELEOPERATOR

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FOREWORD

This report was prepared by Martin Marietta Corporation's Denver Division under Contract NAS8-30266, Configuration and Design Study of Manipulator Systems Applicable to the Free-Flying Teleoperator for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration.

ABSTRACT

A preliminary design of a manipulator system, applicable to a Free-Flying Teleoperator Spacecraft operating in conjunction with the Shuttle or Tug, is presented. The preliminary design is shown to be within today's state-of-the-art as reflected by the typical "off-the-shelf" components selected for the design. A new, but relatively simple, control technique is proposed for application to the manipulator system. This technique, a range/azimuth/elevation rate-rate mode, was selected based upon the results of man-in-the-loop simulations. Several areas are identified in which additional emphasis must be placed prior to the development of the manipulator system. The study results in a manipulator system which, when developed for space applications in the near future, will provide an effective method for servicing, maintaining, and repairing satellites to increase their useful life.

CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF TABLES

I. INTRODUCTION

Plans for extending man's exploration and understanding of space include the use of remotely controlled teleoperators which, when controlled from a safe, habitable location, have the advantage of using man's ability to make decisions as unforeseen conditions arise while contributing significantly to his safety by permitting him to "stand-off" from any hazardous conditions.

Teleoperators, for space application, are generally classified into three distinct systems: (1) Attached Teleoperators; (2) Unmanned Roving Surface Vehicles; and (3) Teleoperator Spacecraft. These systems are extremely complementary in that the first operates solely within the range of a manned spacecraft such as the 15.3 meter (50.0 feet) shuttle attached manipulator presently under study for use in shuttle cargo handling while the sec· operates on lunar or planetary surfaces similar to the Russian Lunokhod. The third system, the teleoperator spacecraft, takes up the gap between the other two systems by enabling the inspection, retrieval, on-orbit maintenance and servicing of payloads separated from the Shuttle. The functional requirements and lead technology items for these teleoperator spacecraft systems are presently being studied and developed by the NASA. One such teleoperator spacecraft system is the free-flying teleoperator spacecraft (FFTS, Ref. 1) referred to throughout this study. It is a typical, experimental prototype to be used for orbital demonstration and evaluation purposes and was selected by this study as the baseline system. This FFTS concept when developed, will comprise one of two Life Sciences Shuttle payloads, the other being a bio-experiment satellite. The FFTS is considered a Life Sciences payload by virtue of the fact it is inherently a man-machine system, depends on man for control inputs, and exists for the purpose of extending man's unique capabilities beyond his physical presence. The FFTS consists of four basic elements: (1) a vehicle, remotely controlled, to provide maneuvering to and from the work site and mobility about the satellite as required; (2) one or more manipulative devices, representative of man's arms and hands, to enable the performance of tasks at the work site; (3) a visual system, analagous to man's eyes, to allow viewing of the work site and task activity; and (4) a control and display station, remotely located in a manned spacecraft or on the surface of the earth, from which the total FFTS mission operations are manually supervised and controlled.

The scope of this present study is to investigate the design of a manipulator system applicable to the FFTS operating in conjunction with the Shuttle. The specific objective, based upon the most promising concept, is to provide a preliminary design of the concept and a preliminary specification document for the FFTS manipulator system.

The study was divided into four tasks as outlined below:

Task 1: Manipulator System Survey - A brief survey of existing hardware components and control modes adaptable to remote manipulators operating in space.

Task 2: FFTS Manipulator System Requirements Analysis - A preliminary requirements analysis to establish the FFTS manipulator system requirements. These requirements serve as a basic input to the conceptual design task.

Task 3: Manipulator Conceptual Designs - A development of manipulator conceptual designs which serve as candidates for the FFTS mission applications. Trade study analyses provide data to enable a selection of a single concept for further consideration.

Task 4: Preliminary Design - A preliminary design of the selected concept supported with engineering analysis, trade studies, and design layouts.

This report summarizes the results of the work performed during this study.

II. MANIPULATOR SYSTEM SURVEY*

The manipulator system survey, Ref. 2, indicated that there exists a wide spectrum of manipulator systems presently being used within the confines of the earth's surface in industrial, hot-lab, and undersea applications as shown by Tables II-1 and II-2. A relatively few systems have been used in space applications such as the Viking Surface Sampler, Surveyor Moon-Digger, and spacecraft deployable booms.

As a result of the survey, it was concluded that most systems were conceived and developed for specific applications. As a particular system became available, new applications for this system evolved and put into actual practice using the identical system. Maximum advantage was taken of the ability to place the control device near the manipulator and, based upon the simplicity of control implementation, the master-slave and switch controlled systems dominated the technology.

In new applications, where operational or environmental constraints existed, i.e., minimizing the operational volume or the bulkhead size for undersea activity, joysticks and switch type control using electrical cable connections to the manipulator actuators were used.

For repetitive type functions, such as assembly line operations, manipulative devices have been designed to augment the operator. These devices are either preprogrammed with the required operations or taught, via the computer/operator, using the "teach" technique. Again, these systems were designed for their specific application.

It is important to note, that several areas of manipulator technology which must be considered in space applications were not necessarily significant design drivers for ground based applications. These in-

* This section presents a brief summary of the Task 1 Final Report (Ref. 2).

Table II-1 Industrial Manipulator Summary

Company	Name	Status	Capability	Remarks
IBM		Developmental		Programable; withdrawn from the market
Unimation	Unimates 2000	Industrial use	68Kg(150lbs)extends 2.42 m(8ft) Accuracy 1.27 x 10^{-2} m (5 mils)	26 units are used by GM for welding on the Vega Assembly line. Standard units have five degrees of freedom with a variable size memory to 1,024 steps. Uses platinum wire memory.
	4000	Industrial use	136Kg(300 lbs)	
AMF	Versatran	In use	To 68Kg(150 lbs)	Uses point-to-point or continuous path control. Hydraulic unit uses positions stored in potentiometers to 4,000 points. Mechanism uses telescoping tubes.
USM		Developmental		Used for parts insertion in the electronic field. Programable using PDP16.
Sunstrand Corp		Used by Dow Chemical	11.35Kg (25 lbs) accuracy (12 mils) repeatability 5.08 x 10^{-3}m (2 mils)	Five-axis manipulator, electrically driven with a 4,096 memory.
Electro-lux Co.(Sweeden)	Material Handling Unit			Programed using electromechanical relays. Pneumatic powered. One model has two arms.
Auto-Place Div. Erie Engineering Corp.	Auto Place	Small parts handler	4.54Kg (10 lbs) 13.6KG (30 lbs)	Pneumatically actuated, programed from a pneumatic logic module.
Burch Controls	Brute		227 to 912KG (500 to 2000 lbs)	Hydraulically actuated
Digital Equip.		Assembly line		Five degrees-of-freedom; two axes hydraulically actuated and three axes are driven with Stepper motors. Minicomputer controlled using a PDP-16. Has 50 program points stored in memory.
Hawker-Siddley (England)				Minicomputer controlled.
Kawasaki Mitsubuski Toshiba (Japan)		Assembly line		Five degrees-of-freedom; two axes hydraulically actuated and three axes are driven with stepper motors. Minicomputer controlled using a PDP-15. Has 50 program points stored in memory.
VFW-Fokker (Germany)	Transferautomat E		30Kg (66 lbs)	Three degree-of-freedom electrically actuated. Programed at patch board with position stored in potentiometers.
Kaufeldt (Sweeden)			Lifts 45.5 Kg (145 lbs) weighs 159Kg (350 lbs) 1.27M(50 in.)reach accuracy: 5.08 x 10^{-3}M (2 mils)	Five degree-of-freedom; programed using electromechanical relays. Can store up to 58 points.
Trallfa Co. (Norway)			Used to enamel bath tubs accuracy 2.03 x 10^{-2}M($\pm$ 8 mils)	Continuous movement, controlled by magnetic tape. Similar to Versatran.
Retab (Stockholm Sweeden)				Advanced system incorporates remote sensing; servo-controlled hydraulically actuated; solid state MOS shift register for memory using 20 2,048 bit chips. Has a search mode that helps locate objects using sensors such as photocells.
Hitachi's Central Research Laboratory	Hi-T Hand Expert 1	Developmental		Two handed, tactile sensing device which is used to insert a piston in a cylinder with a clearance of 20 micrometers. Other models use TV cameras and pattern recognition to find and grasp objects.
Artificial Intelligence Laboratory (Stanford)		Test Bed		Servo-driven, four-foot-long, computer controlled arm with six degrees-of-freedom. Used to assemble small pumps and soon will be programed to assemble a small motor.
Others Syncro Trans. Corp.			9.1Kg(20 lbs) Accuracy 7.4 x 10^{-2}M(30 mils)	These manipulators are in general limited in the number of functions they can perform, and they cost less than the others discussed.
Robotics Prab Engineering Corp.			2.3Kg to 23Kg (5 to 50 lbs)	
Wickes Machine Tool Division			45.4Kg (100 lbs) rated	

Table II-2 Undersea Manipulator Summary*

Vehicle	Type of Manipulator	Control Summary	Capabilities
ALUMINAUT	Two Arm, Hydraulic, 6 Degrees-of-Freedom (DOF)	Two Joysticks for each arm: Fine - Elbow Wrist Coarse-Shoulder	91Kg at 2.7 m (200 lb at 9 ft) Reach
ALVIN	One Arm, Electric, 6 DOF	Toggle Switch Adjustable Grip Force	22.6 Kg at 1.5 m (50 lb at 5 ft)
BEAVER IV	Two Arm, Hydraulic Proportionate, 8 DOF	Joystick Proportionate Rate Control	Tool Exchange; 12.7 KG at 1.8 m (50 lbs at 6ft)Reach; Four Alternate Mounting Positions
DEEP QUEST	Two Arm, Hydraulic, 7DOF	Toggle Switch Adjustable Rates	45.5 Kg at 2.1 m (100 lb at 7 ft); Variable Positioned Base, Retractable
DEEP STAR 4000	One Arm, Hydraulic, 3 DOF	Joystick Rate Control	1.1 m (3.5 ft) Reach ; 16 Kg (35 lb) Lift
DIVING SAUCER COUSTEAU	One Arm, Hydraulic, 2 DOF	Joystick Rate Control	
DOWB	One Arm, Electrical, 6 DOF	Toggle Switch, Two-Speed Rate Control Selectable Grip Force	Optics, TV, 1.2 m (49 in) Reach; 22.6 Kg (50 lb) Lift
DSRV-1	One Arm, Hydraulic, 7 DOF	Selectable Joint, Position Control, Joystick, Adjust Grip Force	2.3 m (7.5 ft) Reach; 22.6 Kg (50 lb) Lift; Multiple Tool; Permanently Mounted
DSRV-2	One Arm Hydraulic	Rate Control, Auto Stowage	2.5 m (7.5 ft) Reach; 22.0Kg (50 lb) Lift; Multiple Tool; Permantly Mounted
RUM	Remote, Electric Motor, 5 DOF	Remote Rate Control, Four TV Cameras	226Kg at 2.1 m (500 lb at 7 ft); 22.6 Kg at 4.6 m (50 lb at 15 ft)
SEA CLIFF & TURTLE	Two Arm, Hydraulic 7 DOF	Push Button Rate Control, Selectable Rates	54.5 KG at 2.3 m (120 lb at 7.5 ft); Tool Exchange
STAR II	One Arm Hydraulic, 4 DOF	Push Button Rate Control	22.6 KG at 1.2 m (50 lbs at 4 ft)
STAR III	One Arm Hydraulic, 6 DOF	Push Button Rate Control	68.1 Kg at 2 m (150 lb at 6.5 ft)
TRIESTE 1	One Arm, Electric 6 DOF	Push Button Rate Control	22.6 Kg at 0.7 m (50 lb at 29 in)
TRIESTE II	One Arm, Hydraulic 7 DOF	Push Button Rate Control, Grip Adjust Variable Rate	Several Arms Fitted to This Vehicle at Various Points in Time
CURV	One Arm (Claw) Hydraulic 3 to 4 DOF Remote	TV Camera	Turret Mounted; 91Kg (200 lb) Maximum Lift; 2.7 m (9 ft) Reach; 43KG (95 lb) Average Lift

*(Ref. 3)

cluded: (1) the lack of direct operator viewing; (2) the impact resulting from large computational requirements; (3) the desire to perform general purpose rather than specific, repetitive, or automatic type operations; (4) the minimization of the operator workload (since operators can be relieved when tired); and (5) transmission link time delays resulting from physical separation of the manipulator and the control device; (6) reliability of operating in space; and (7) the manipulator/work site interface. Each of these areas provides a new challenge to the expanding field of manipulator technology as reflected by the new control techniques being proposed.

A significant conclusion resulting from this survey was that whether the manipulator system is presently an off-the-shelf item, a special application type design, or in the conceptual stage, all the components, sensors, devices, etc., used or proposed were within the present state-of-the-art. The major concern is basically proving the feasibility of the technique and developing the technique into a practical design.

Additionally, it was noted that, in general, the manipulator configuration impacted the controller design and the control laws implemented. This interrelationship was so prominent that to design a manipulator without considering the control laws and controllers to be used, as well as the tasks to be performed and the man-machine interface required, may result in an excessively complex system.

III. PRELIMINARY REQUIREMENTS ANALYSIS*

A preliminary requirements analysis for manipulator systems, applicable to the FFTS operating in conjunction with the Shuttle and Tug, was performed. The requirements analysis investigated two types of manipulator systems: a general purpose manipulator having the primary function of on-orbit servicing and maintenance of satellites and a retrieval type manipulator for use in support of satellite deployment and retrieval applications, which included the spinup of deployable satellites and the dynamic passivation of spinning/tumbling satellites.

A summary of the requirements established (Ref. 4) are shown in Tables III-1 through III-3. The requirements were developed as a result of derivations, assumptions, estimates, technical judgment, and general guideline considerations. In addition, the results of a recent study, Shuttle Remote Manned Systems Requirements Analysis, NAS8-29904 (Ref. 5) were incorporated.

Several significant aspects were identified during this analysis. For example, while the FFTS docking device was initially considered somewhat unrelated to the manipulator preliminary design study, a reduction of both the general purpose manipulator and visual sensor articulation complexity resulted when the FFTS docking device contained either docking symmetry or continuous rotational features; e.g. rotate or redock the FFTS, via the docking device, to reposition the manipulator at a new work site as opposed to providing the manipulator with the additional reach capability.

A review of the requirements also indicated that the general purpose and retrieval type manipulators had certain areas of commonality such as reach, mass, and torque. Additionally, it was shown that the general purpose manipulator could provide retrieval capability for all identifiable nominal satellite dynamic states. Only in cases where off-nominal dynamic states or contingency type failures occur was a dedicated retrieval type manipulator required.

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* This section presents a brief summary of the Task 2 Final Report (Ref. 4).

Table III-1 Program Critical Spacecraft Requirements Summary

Item No.	Spacecraft Applicable Subsystem	Selected Requirements and Characteristics
1.0	Shuttle Orbiter	
	Payload Bay Size	18.3 m x 4.6 m dia, (60 ft. x 15 ft. dia)
	Payload Launch Capability	29,500 Kg @ 28.5° Incl/365 km (200 n.mi)
	Payload Power Allocation	50 Kw from fuel cells
	Power Interface	28 VDC nom. + 2.5 - 4 VDC
	Cont. Supply	1 Kw average, 1.5 Kw peak
	Special Supply(Max.)	3 Kw average, 6 Kw peak
	Data Cmd. Allocations	RF communication + TDRS Medium Band Link
	Orb. to Satellite	2 Kbps
	Satellite to Orb.	2 Kbps
	Envrn., Bay area	
	Launch/Entry Load	3G's for 30 minutes
	Design Load for Fittings	12 G
	Acoustic	N/A
	Shock	N/A
	Pressure	Sea level through synchronous altitude, zero-gravity
	Temperature	-73 to 93°C (-100 to + 200°F)
	Humidity-Air	0 to 43 grains/pound of dry air
	Shuttle/FFTS Interface	FFTS Berthing Station in Shuttle Bay
	Service interface by Shuttle	Electrical, mechanical, (mounting, deploy and retrieve) & fluid (refueling)
2.0	Shuttle Payloads	
	Size Range	0.5 - 4.3 m (1.6 - 14 ft) dia x 0.6 - 17.7 m (2-58 ft) Long
	Weight Range	90 Kg (200 lb) Satellite to 20,400 Kg (45000 lb) Sortie
	Dynamics, Spin Rate	<60 rpm
	Payloads/Shuttle Flight	1-5
	Payload Support Functn.	
	Deploy/Retrieve	Provide FFTS axis of attach. along satellite spin or tumble axis
	Servicing	Module Remove/Replace, Connect/Disconnect, etc.
	Satellite Serviceable Modules	
	Sizing (Maximum)	1 x 1 x 1 m (3.3 x 3.3 x 3.3 ft)
	(Minimum)	0.15 x 0.15 x 0.15 m (0.5 x 0.5 x 0.5 ft)
	Weight (Maximum)	150 Kg (330 lbs)
	Satellite/FFTS Capture by SAMS	Cooperative capture
	Study Ref. Satellites	LST, LDEF, EOS and BES
3.0	FFTS	
	Size	0.9 x 0.9 x 1.5 m, (3 x 3 x 5 ft)
	Weight(Spacecraft)	182 Kg (402 lb)
	Reliability	FFTS will be designed to be fail safe
	Safety	No single point failure in subsystem shall cause a catastropic FFTS action.
	Removal from Bay	Compatible with SAMS for on-orbit removal
	Return to Bay	Capture by SAMS requires FFTS to maintain following:
	Longitudinal velocity	0.015 m/sec (0.05 ft/sec)
	Lateral velocity	0.015 m/sec (0.05 ft/sec)
	Angular misalignment	$\pm$ 0.009 rad ($\pm$ 0.5 deg)
	Angular rate	0.0175 rad/sec (1 deg/sec) maximum
	Insert/remove position	Horizontal for Shuttle Orbiter, Vertical on launch pad
	Target capture capability	Target position is known to $\pm$ 1.852 Km 3σ in each axis
	Specified Traj. accur.	Within 5% or 0.5 m (1.6 ft)
	Translation range	Up to 5000 m (16,500 ft) loaded
4.0	Tug	Information on initial and final tug has been combined
	Size (Length & Dia.)	9.7 x (3 to 4.5) m, (32 x (10-15) ft)
	Payload; Size(Length)	7.6 m (25 ft)
	Payload Delivery	1590 Kg (3,500 lb)
	Power	0 - 300 watts while attached
	Mission	Deploy, retrieve and service
	Communication Data	2 Kbps CMD, 2 Kbps TM
	Satellite Servicing Unit (SSU)	Provide automatic satellite servicing
	Space Replaceable Units (SRU's)	
	Number of SRU's	40 standard units
	Weight range	9 to 109 Kg (20 to 240 lb)

Table III-2 FFTS Manipulator System Subsystems Requirements Summary

Item No.	Subsystem & Elements	Requirements & Characteristics: General Purpose Manipulator	Requirements & Characteristics: Retrieval Manipulator
1.0	Structure		
	Arm Configuration	Modular	Modular
	Segments	2	1-2
	Length	2-3 meters	3 meters max.
	Diameter	TBD	TBD
	Working Reach	2-3 meters	3 meters
	Weight	11.3 Kg (25 lbm)/m	11.3 Kg (25 lbm)/m
	Deg. of Freedom(thru wrist)	3-8	2-6
	Working Volume	Hemispherical over docking interface	Circular in front of FFTS
	FFTS Attach Interface	Interchangeable	Interchangeable
	Weight of Module Held	150 Kg (330 lbm)	TBD
2.0	End Effector	Clamp or Insert	Clamp
	Jaw	Engage,Hold and Release	Engage, Hold & Release
	Grasp Width	10-16 cm max.	10-16 cm max.
	Grasp Depth	3.8 cm min, 10 cm max.	15 cm max.
	Grasp Force	44.5-89N (10-20 lbs)	44.5-89N (10-20 lbs)
	Deg. of Freedom	1	1
	Inter, Electro Mechanical	Interchangeable	Interchangeable
	Length, Unit	TBD	TBD
	Weight Unit	11.3 Kg (25 lbm)/m	11.3 Kg (25 lbm)/m
3.0	Actuators		
	Type Units	Electro Mechanical	Electro Mechanical
	Power	28 ± 4 Volts	28 ± 4 Volts
	Output Velocity	Cont. Var. from 0-max. loaded	Cont. Var. from 0-max. loaded
	Wrist/End Eff. Inter.	Cont. Rotation	Cont. Rotation
4.0	Sensors	Force, Feel & Visual	Force, Feel & Visual
	Force, EE Wrist & Arm	TBD	TBD
	Feel, EE	Electrical	Electrical
5.0	Control Electronics	TBD	TBD
6.0	Controllers	(Replica, Exoskeleton & Hand)	TBD
7.0	Control Schemes	(Open)	TBD
8.0	Manipulator System		
	Length	2-3 meters	3 meters, max.
	Spinup & Despin	-	0 to 60 rpm
	Applied Torques	20.22 N-M (15 ft-lbs)	20.22 N-M (15 ft-lb)
	Motion Arrest Time	-	12 minutes, max.
	Tip Force, Full Ext.	45.5 N (10 lb) min.	44.5 N (10 lb) max.
	Tip Speed, Maximum Full Ext.	0.6 M/sec (2.0 ft/sec)	3 M/sec (9.9 ft/sec)

Table III-3 FFTS Subsystems Requirements Summary

Item No.	Spacecraft & Elements	Selected Requirements & Characteristics
1.0	FFTS (Spacecraft located)	For System Level see Table III-1
	Size, Baseline	0.9 x 0.9 x 1.5 m (3 x 3 x 5 ft)
	Weight (Spacecraft)	182 Kg (402 lbm)
2.0	Docking Device	Primary location on front surface of FFTS
	FFTS/Satellite Separation	≤2 m (6.1 ft)
	Satellite End Docking	Manipulator capable of reaching cylindrical edge of satellite
	Satellite Side Docking	Multiple docking location
	Docking Reposition	Consider 120° positional symmetry
	Closing Velocities, Axial	0.03 to 0.305 m/sec (0.1 to 1.0 ft/sec)
	Lateral	0.0 to 0.152 m/sec (0.0 to 0.5 ft/sec)
	Angular	0.0 to 0.0175 rad/sec (0.0 to 1.0 deg/sec)
	Misalignments, Radial	Up to 0.305 m (1 ft)
	Angular	± 0.087 rad (± 5 deg)
	Rotational	± 0.087 rad (± 5 deg)
3.0	Visual Sensors	Provide coverage of all manipulator activity
	Sensor to worksite distance	Articulated to at least 1 m (3.28 ft)
	Transmission Time Lag	0 - 6 seconds
	Sensor Field of View	0.12 to 0.7 radians (7 to 40 degrees)
	Sensor Articulation	Provide 4π steradians coverage; 1 meter min. range
	Sensor Sensitivity	Maximum threshold - 60 ft - lamberts
	Transmitted Frame Rate	≥12.5 frames/sec
	Displayed Frame Rate	≥15 frames/sec
	Resolution	Task performance - 100 line pairs horizontal/vertical
	Bandwidth	500 KHz
4.0	Guidance/Navigation & Cont. (GNC)	
	Assure Relative Attitude	± 0.00044 rad (± 0.025 deg) about orthog. rot. axis
	Attitude Rates	±0.00022 rad/sec (±0.0125 deg/sec) ortho. rot. axis
	Provide Control Info. Within:	
	Relative position	± 0.05 m (± 0.017 ft) on orthogonal ref. trans. axis
	Relative velocities	± 0.015 m/sec (± 0.05 ft/sec) on orthogonal ref. translation axis
	C.g. offset immunity	± 150% about any axis
	Nav. and Tracking accuracy	0.0305 m (0.1 ft) or 0.1% at a max. range of 3000 m (9800 ft) from a primary tracking station
5.0	Propulsion/Reaction Control	
	Total Impulse	66,800 N-sec (15,000 lb-sec)
	Provide Propellant Off-load	FFTS berthing station with doors open or closed
	Emergency propellant venting	Use non-propulsive vents and direct away from any objects being handled or transported
	P-R-Y Attitude Hold Accur.	± 0.0018 rad (± 0.01 deg) either loaded or unloaded
	X,Y,Z Trans. Hold Occur	± 0.0032 m (± 0.25 ft)
	Velocity Change Capability	Total ΔV is 30.5 m/sec (100 ft/sec)
	Attitude Change Capability	Total Δω is 20π rad (3600 deg)
	Translating Capability	5000 m (16,400 ft)
6.0	Power, Electrical	
	FFTS Load	610 watt hours
	Voltage	28 VDC non, to ± 4 VDC
	Mission Time Duration	2.5 hour nom.
	Warmup + Checkout Time	20 minutes max.
	Rated Discharge Time	Minimum 1.0 hours
	Recharge Time	16 hours
	Temperature Range Operating	-40 to + 165°F
	Recharge Cycles	80 cycles
	Batteries	Dual battery banks
	Total Battery Energy Source, Weight	26.4 lb
	Total Battery Energy Source, Volume	1.7 cu ft.
	Load buses	2 parallel critical load buses + 1 non-critical
7.0	Subsystem (Shuttle Located)	
	Size Baseline	TBD
	Weight (Baseline est)	227 Kg (500 lb)
8.0	Specialized Computation	
	Autonomous Control Features	Stabilization, navigation, manipulation, etc.
	Interf. Interrogation Rate	At least 20 samples/sec.
	Computation Cycle Time	0.017 sec

Table III-3 (Cont'd)

Item No.	Spacecraft & Elements	Selected Requirements and Characteristics
9.0	Central Data Relay Net (CDRN)	
	Basic Elements of CDRN	Shuttle Orbiter, Space and Ground Tracking, etc.
	FFTS Communication Window	Minimum of 1200 sec
10.0	Communications & Data Mgt.	
	Bandwidth	
	CMD: Manipulator	1 kbps minimum to 20 kbps derived maximum
	Platform	1 kbps minimum to 2 kbps derived maximum
	TEL: Manipulator	0.01 kbps
	Platform	2 kbps minimum to 4 kbps derived maximum
	Video	27 kbps minimum to 17,000 kbps derived maximum
	Telemetry Range Total	30 kbps minimum to 17,000 kbps derived maximum
	Comm.Range(Orbital Cmd. Stn)	0.5 to 10,000 m (1.6 to 32,800 ft)
	Relative Velocity(maximum)	300 m/sec (1000 ft/sec) Co-orbiting Elements
	Carrier Frequency Band	S-Band primary (X or K)
	Communication Window(Min)	1200 sec.
	Time Delays: Propagation	0.12 to 0.3 sec
	Video Process	Up to 6.0 sec
	Orbital Coverage (TDRSS)	
	Minimum Coverage	85% for 200 km
	Other Coverage	100% between 1200-2000 km
11.0	Control and Display Station	Assume located in Shuttle Orbiter (most restrictive)
	Location Considerations	Shuttle, sortie-laboratory and on the ground
	Man/Machine Interface	Operator/console, operator/controller & operator/restr
	Anthropometry Considerations	Accommodate 5th to 95th percentile male
	Number of Operators at CDS	Consider one operator as a design guideline
	CDS Configuration	Assume basic configuration reported in Ref. 7
	Physical Configuration	Use Fig III-5 as study baseline
	Operator/Console Envelope	TBD
	Console Weight	48 kg (106 lb)
	Operator/Console Dimensions	
	Basic Assumption	Fixed eye - head position for all sizes of operators
	Eye to primary displays	55.5 cm (22 in) along line-of-sight
	Eye to secondary displays	33 to 75 cm (13 to 29½ in)
	Horizontal line-of-sight	Perpendicular to vertical body axis
	Panel viewing line-of-sigh	0.26 rad (15 deg) below horizontal line-of-sight
	Functional reach	63 cm (25 in) from arm pivot point (5th % male)
	Restraint (minimum)	Waist/lap belt and toe bar
	CDS Panel Surface Area	Ranges from optimum to acceptable
	Optimum Area	1265 sq. cm (196 sq. in)
	Peripheral, Optimum	2715 sq. cm (420 sq. in)
	Acceptable Area	Ranges from 2840 (440 sq. in) to 12,650 (1960 sq in)
	Manipulator Controller Loc.	TBD
	Operator/Controller Dim.	
	Eye to Elbow	Use 56.4 cm (22.3 in), 95th percentile male
	Elbow to Handgrip	Use 37.6 cm (14.9 in), 95th percentile male
	Manipulator Contlr.Handgrp	Assume comfort position of 95th percentile male
	Controller Neut. Pos. Ref.	Arm at side with 1.56 rad (90 deg) bend at elbow
	Controller Operating Env.	Assume optimum volume for operator comfort
	Horizontal movement	15.3 cm (6 in) radius from neutral position
	Vertical movement	20 cm (8 in) up to 15.3 cm (6 in) down from neut. pos.
12.0	Safety	
	Imposed Requirements	Space Shuttle related activities will comply with NHB-5300
	Potential Hazard Areas	These areas will be designed with fail safe features
	RCS/Propulsion Hardware	Will have factors of safety as per MSFC-HDBK-505

IV. MANIPULATOR SYSTEM CONCEPTUAL DESIGNS

This section describes the results of the work performed during Task 3 of the study, Manipulator System Conceptual Designs. The objective of this task was to generate conceptual designs which can serve as candidates for the FFTS mission applications including both satellite servicing and retrieval.

The conceptual designs were developed considering primarily the four major elements of the manipulator system: configuration, controller, control method, and end-effector.

A. MANIPULATOR CONFIGURATIONS

Configuration concepts were divided into two categories, a General Purpose manipulator for satellite servicing applications and a Retrieval Type manipulator for satellite retrieval. The General Purpose manipulator is discussed on increasing complexity from concepts with minimum degrees-of-freedom (D.O.F.) to concepts with more than six degrees-of-freedom. In each concept discussed there are a number of options which can be incorporated to increase the reach. These options, however, require additional DOF's. The Retrieval Manipulator concepts are discussed in terms of the satellite dynamic state - stable, spinning, and spinning/tumbling. It should be noted, however, that the Retrieval manipulator is a special case of the General Purpose manipulator and, in many instances, the General Purpose manipulator is able to perform the retrieval tasks. Thus, the analysis used for the General Purpose Manipulator directly applies to the Retrieval Manipulator.

1. General Purpose Manipulator - Less Than Six Degrees-of-Freedom

The minimum DOF General Purpose manipulator consists of an arm which only pivots about the base as shown in Fig. IV-1. In this configuration, the number of modules that can be serviced is limited to modules located on the arc in stacking order. In order to service more modules the FFTO must redock or rotate with respect to the satellite at the docking interface. If the module/satellite interface requires that the modules be removed with a motion perpendicular to the satellite end, then the manipulator must incorporate an additional DOF, typically an extension shown in Fig. IV-1.

Also shown in Fig. IV-1 is a two DOF concept utilizing a turret mechanism that rotates and extends. Following the docking of the FFTS to the spacecraft, the docking device will rotate the FFTS to align the extendible boom with the particular module to be removed from the spacecraft. The boom is extended and the end effector grasps and unlocks the module. The extendible boom retracts, removing the module until clear of the spacecraft. The turret then rotates until the module is aligned with an empty storage rack. The boom extends placing the module in the rack and is locked-in. The boom is then rotated to pick up the replacement module in one of the other rack positions. The procedure is now reversed to place the new module in the spacecraft. A preliminary conceptual design of the mechanism involved in this type of manipulator is illustrated in Fig. IV-2. The extendible boom is operated by using a common ball screw device complete with a motor driven gear train to achieve the speed and force desired. The boom is stabilized through the cam roller guide located forward of the drive. The turret drive is located directly under the ball screw drive and rotates.

Additional concepts, in which the base of the turret mechanism is moved with respect to the FFTS, provide an increase in manipulator reach and working volume. Thus the number of modules serviced is easily extended. The concepts can use various mechanisms to accomplish the increased coverage.

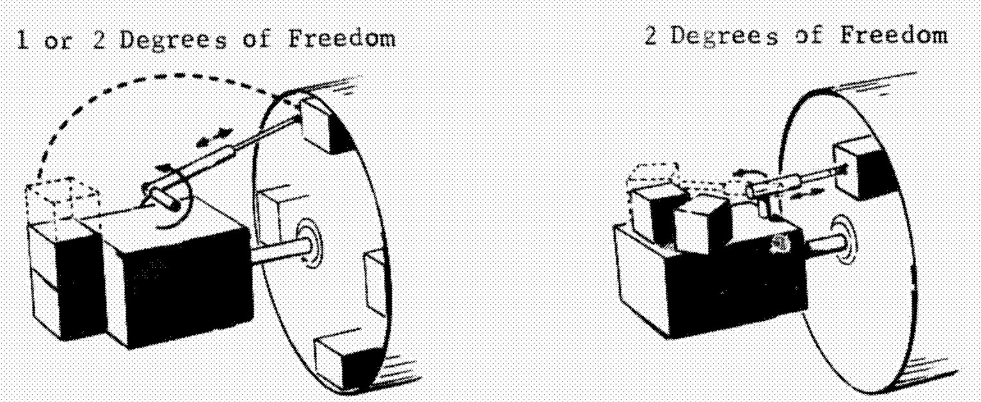


Figure IV-1 Minimum-Degree-of-Freedom Servicing Manipulators

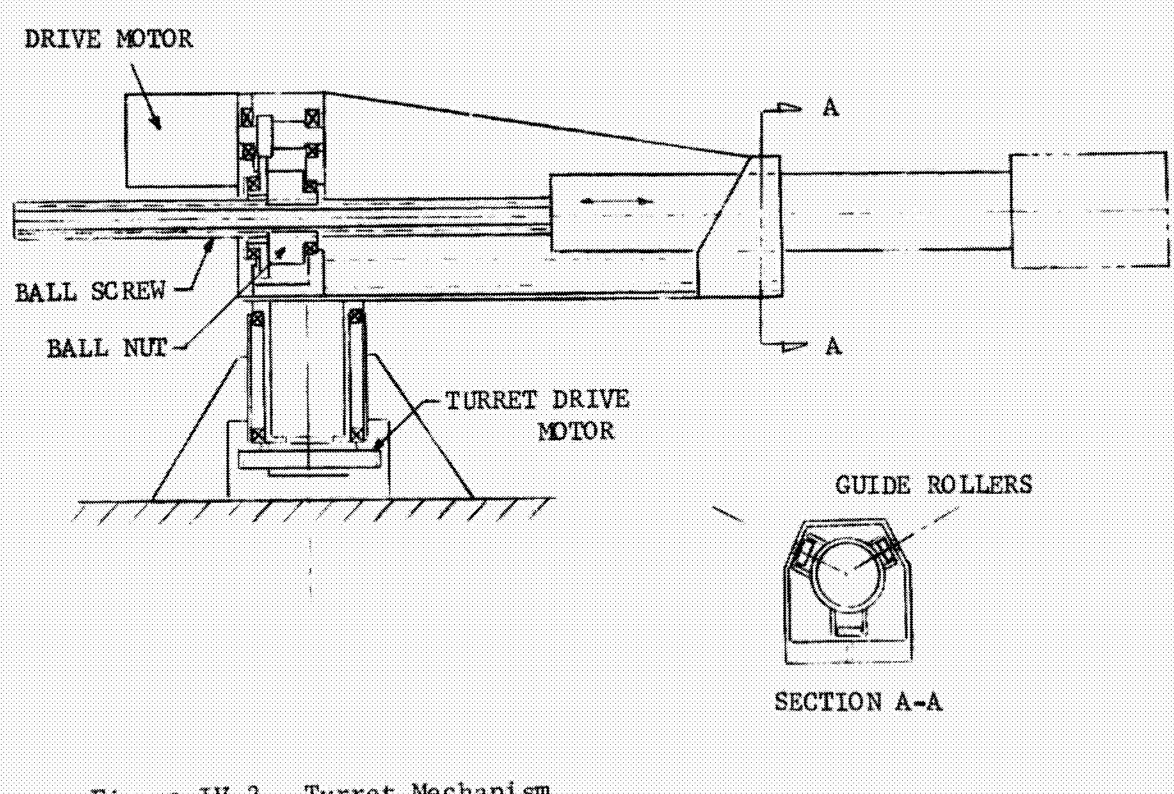
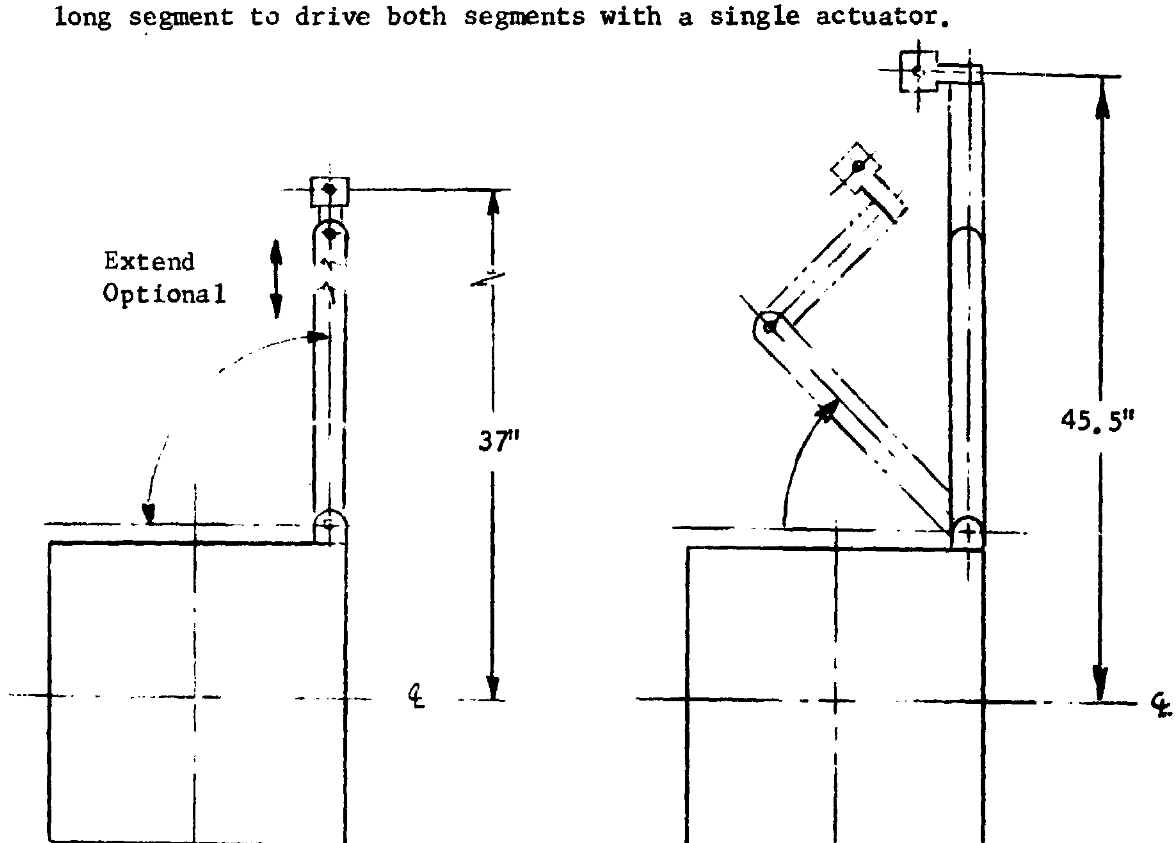


Figure IV-2 Turret Mechanism

Two concepts are illustrated in Fig. IV-3. The first is a single segment arm which provides additional positioning capability to the turret drive. An alternate technique is to replace this articulated segment with an extendable member. In this case, the turret device will remain parallel to the FFTS centerline regardless of extended position. The second consists of a double segment arm of unequal lengths. long segment passes across the full width of the FFTS, and pivots at its base. The short segment pivots around the opposite end of the long segment such that as the long boom rotates $\pi/2$ radians, the short boom travels π radians. Thus, at full deployment the two segments are in line with each other for maximum reach. The short segment actuation is accomplished through parallel bar linkages running the full length of the long segment to drive both segments with a single actuator.



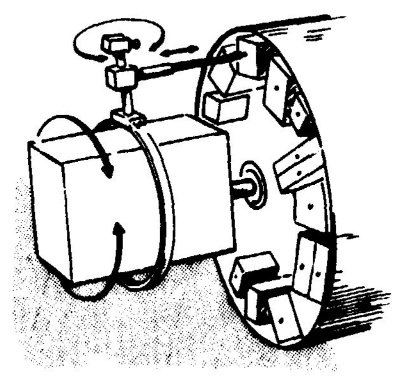
a) Single Segment Arm with Turret

b) Double Segment Arm with Turret

Figure IV-3 Articulated "Turret Drive" Concepts

It should be noted that, as in the case of the two DOF concept, these concepts all require that the modules be stored on an arc about the rotation point at the base of the turret which is a significant disadvantage if the number or volume of the modules becomes large.

Concepts which provide additional servicing capability are shown in Fig. IV-4. These concepts are alternate methods of moving the turret

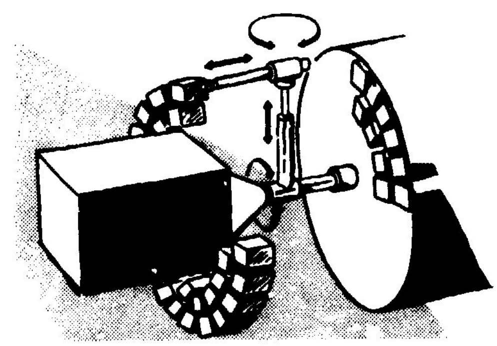


ADVANTAGES
SIMPLE MECHANISM
SIMPLE CONTROL
LIGHTWEIGHT

DISADVANTAGES
ONE SURFACE SERVICED
FLEXIBLE MECHANISM
TOLERANCE SENSITIVE

OPTION: 1. EXTEND TURRET IN THE VERTICAL DIRECTION TO ACCOMMODATE TWO ROWS OF MODULES.
2. TURRET IS FIXED AND RELATIVE ROTATION IS ACHIEVED AT THE DOCKING INTERFACE AND THE FFTS MODULE RACK.
3. COMBINATION OF 1 and 2.

(a) Circular Track with Turret, 3-DOF



ADVANTAGES
SIMPLE MECHANISM
SIMPLE CONTROL
LIGHTWEIGHT

DISADVANTAGES
ONE SURFACE SERVICED
FLEXIBLE MECHANISM
TOLERANCE SENSITIVE

(b) Cylindrical Coordinate Servicing Mechanism, 4-DOF

Figure IV-4 Cylindrical Coverage Concepts mechanism in lieu of rotating the docking device or repositioning the FFTS to obtain complete coverage of the cylindrical end of the satellite. With the Circular Track concept, the turret is driven around the track through a motor driven gear pinion drive mounted on the track and beneath the turret. The extendible boom extends to the module to be removed. The end effector attaches to the module, unlocks the module and places the module into an open stowage rack located in front of the track. The extendible turret would then be indexed to a new position where the replacement module and extendible turret are aligned. The end effector would then attach and unlatch the module from the FFTS, move the module into the open spacecraft cavity and lock the module in place.

The second concept in Fig. IV-4, in which the manipulator is mounted on the docking device, provides essentially the same motion as the circular track concept without the track and track support weight. A similar concept, proposed by MSFC, is shown in Fig. IV-5. The carrier vehicle in this case is the tug rather than the FFTS. Also, the radial arm is supported at the periphery which results in a less flexible mechanism.

These 3-4 DOF concepts are relatively simple, lightweight, and small mechanisms that potentially can se[illegible]ce many modules. However, these devices complicate the d[illegible]ck-ing mechanism and requir[illegible] long docking probe to pro[illegible]

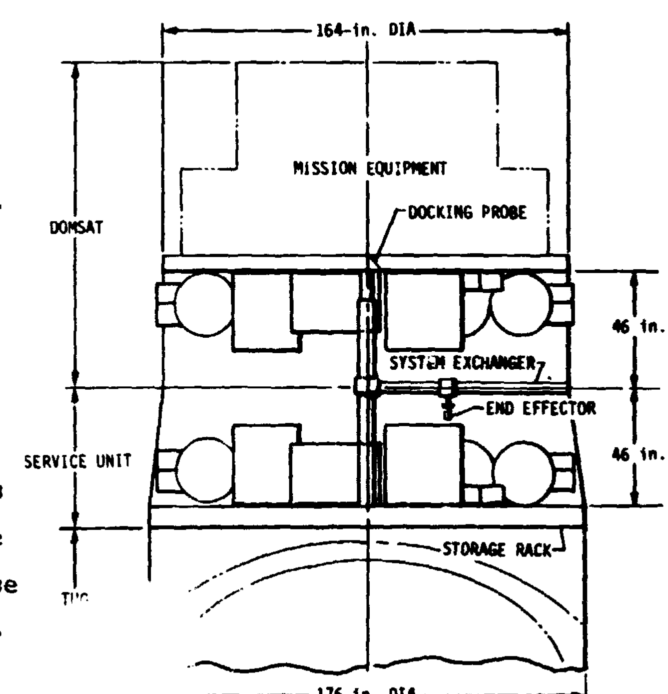
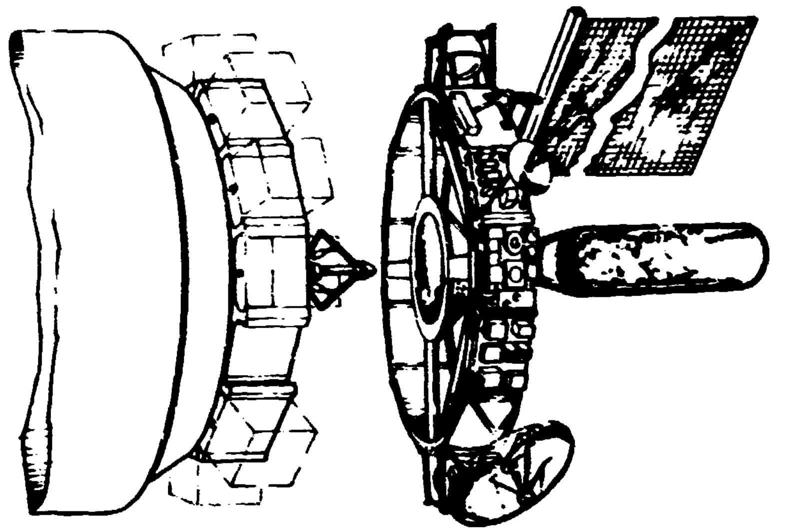


Figure IV-5 MSFC 4-DOF Mechanism Concept adequate separation distance between the FFTS and the satellite. Furthermore, the satellite interface must be relatively free of surface obstructions or protrusions that may interfere with the turret motion.

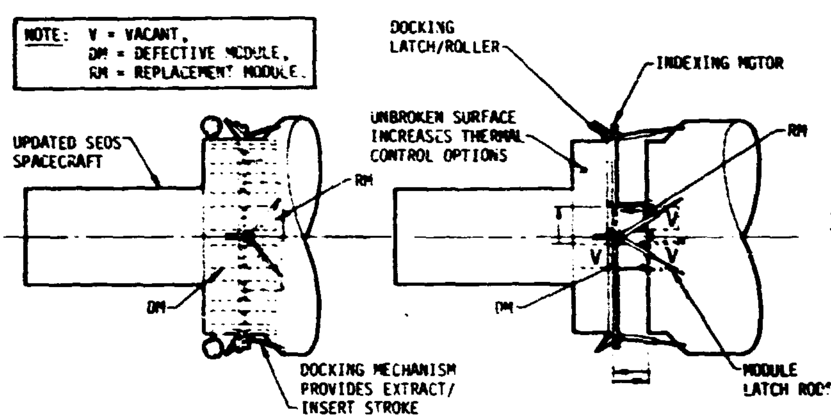
Servicing concepts proposed by others are shown in Figs. IV-6 and IV-7. The Space Service concept is proposed for the Defense Systems Program (DSP) satellite. While the concept appears at first glance to involve only one degree of freedom, it also requires a rotatable docking interface for a second degree of freedom. A MDAC version of this concept is also shown in Fig. IV-6 where the docking mechanism provides rotary indexing and axial motion to exchange the modules.

A Bell Aerospace concept which has received detailed investigation for use with Tug is shown in Fig. IV-7. Prior to docking the turret is moved to one side and the docking device is extended through the opening. After docking the extension mechanism is retracted and the module rack is secured to the satellite body. The turret moves in cartesian coordinates plus a rotation at the base. The mechanism offers simple control, rigidity, and one-to-one module replacement but the structure, extendible docking mechanism, and weight appear to penalize the concept with regard to the working volume. This same working volume can be provided with one of the lighter weight cylindrical coordinate mechanisms previously discussed.

Another concept providing a larger module storage volume, by enabling module replacement normal to the satellite cylindrical surface (for small diameter satellites), and module replacement on the end of the satellite (for large diameter satellites) is shown in Fig. IV-8. This concept is also similar to one proposed by General Electric for servicing the advanced geostationary operational environmental satellite (AGOES). Again, in order to provide coverage about the satellite, the docking device must rotate. The boom concept, however, does not provide the volume that could be achieved if the boom segments were

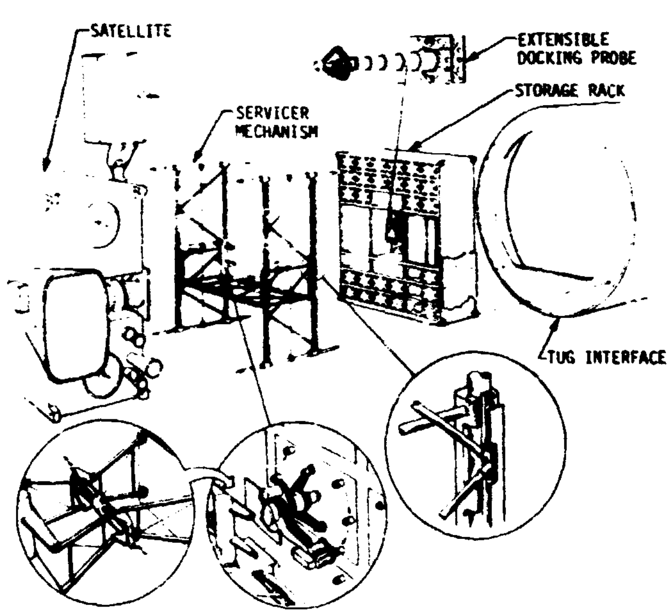


Space Servicing
DSP Concept



Direct-Access
Servicer

Figure IV-6 Space Service and Direct-Access Concepts



ADVANTAGES
RIGID MECHANISM
SIMPLE CONTROL

DISADVANTAGES
ONE SURFACE SERVIC
COMPLEX MECHANISM
HEAVY
TOLERANCE SENSITIVE

Figure IV-7 Bell Aerospace Cartesian Coordinates Servicing Mechanism

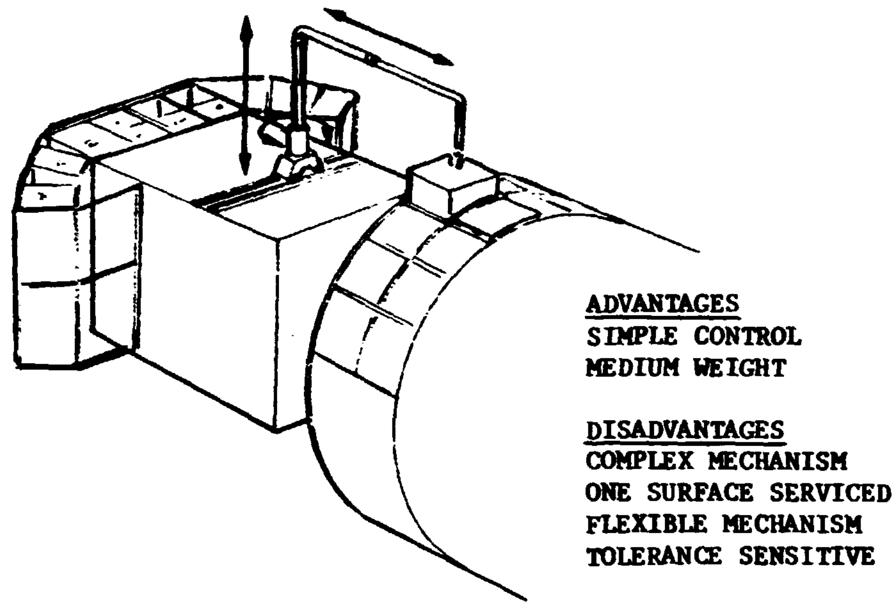


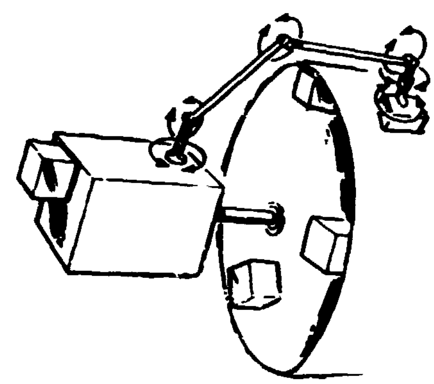
Figure IV-8 Boom Concept

driven in a different manner, namely a full motion manipulator.

2. GP Manipulator - Six Degrees of Freedom

The 6 DOF manipulator allows full motion of the tip or end effector in a sphere of radius determined by the total manipulator length and provides in general, 3 DOF translational/3 DOF rotational capability. Typically, a 6 DOF manipulator as illustrated in Fig. IV-9, allows multiple surfaces on the satellite to be serviced from a single dock, is insensitive to obstructions on the satellite surface, can service a large number of modules with various sizes and shapes, provides a large working volume and, with man-in-the-loop, is less tolerance sensitive. In addition to having the reach to service a large volume on the satellite, the manipulator also has the potential to store modules on or in more than one surface of the FFTS. This concept is representative of what is generally referred to as a general purpose manipulator system.

As with other concepts there are a number of options which can be used to increase the manipulator reach and operational volume with respect to the satellite. For example, if the docking device incorporates an extension, rotation, and articulation, the working volume is greatly increased. As shown in Fig. IV-10, the manipulator arm in this configuration provides fairly complete coverage of the representative class of satellites (Ref. 5) to be serviced by the FFTS.



ADVANTAGES
MULTIPLE SURFACES SERVICED
MEDIUM WEIGHT
TOLERANCE INSENSITIVE

DISADVANTAGES
COMPLEX CONTROL
COMPLEX MECHANISM
FLEXIBLE MECHANISM

Figure IV-9 Full-Motion Servicing Mechanism, 6-DOF

As a result of the flexibility provided by a 6 DOF manipulator system, a preliminary analysis of the number of possible combinations of joints and/or extensions was conducted to establish a preferred concept. The analysis, contained in Appendix A, trades-off 64 possible combinations of 6 DOF gimbal sequences and evaluates extendable vs articulated joints. The preferred concept is shown in Fig. IV-11.

General Purpose Manipulator-More Than Six Degrees of Freedom

A 6 DOF general purpose manipulator is the simplest configuration from both a mechanical and control standpoint to allow positioning of the manipulator end point. The preferred six DOF system does, however have disadvantages. For example, motion of the elbow results in motion of the wrist, and the second and third rotations are about the same axis so that both arm segments are in the same plane. Both are potential disadvantages when working near satellite obstacles or protrusions.

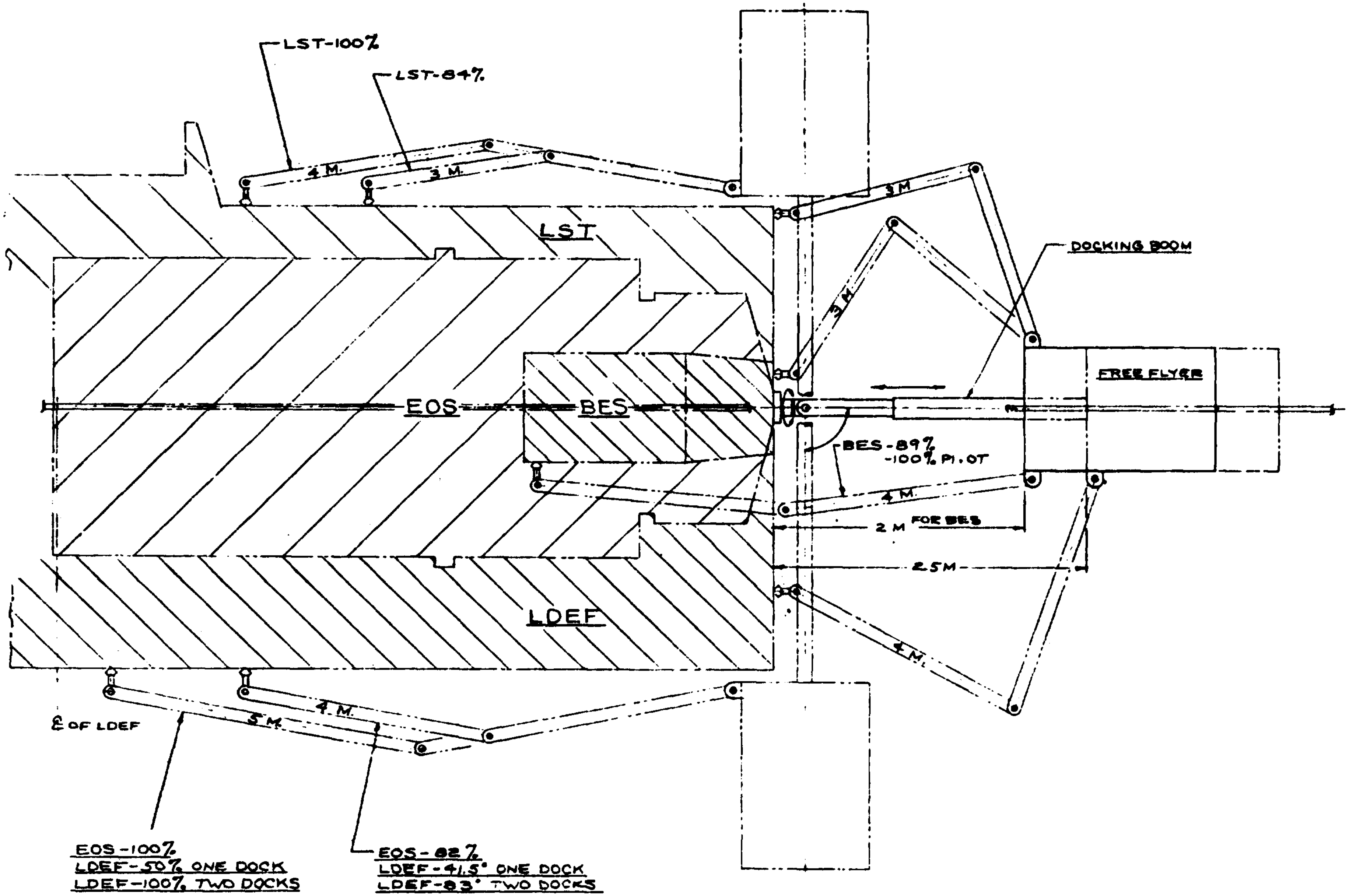


Figure IV-10 Manipulator with an Extendible, Articulated Docking Device

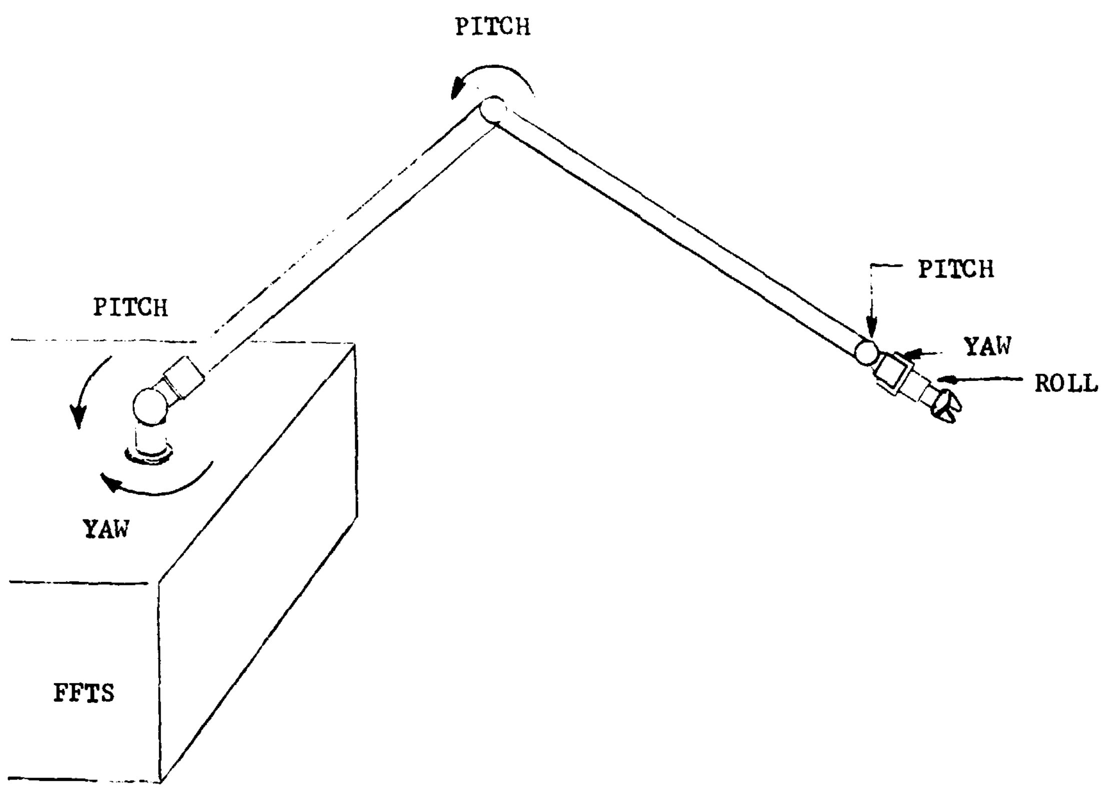


Figure IV-11 Preferred 6 DOF Manipulator Concept

A manipulator with more than 6 DOF, depending on the configuration, can reach behind surfaces or can be used to reduce the effective manipulator length as illustrated in Fig. IV-12. The disadvantages of a system with more than six DOF are: (1) an increase in weight due to the additional mechanization and (2) the tip position is no longer a unique set of joint angles and extensions. In fact the joint angle and length "set" may be many times redundant.

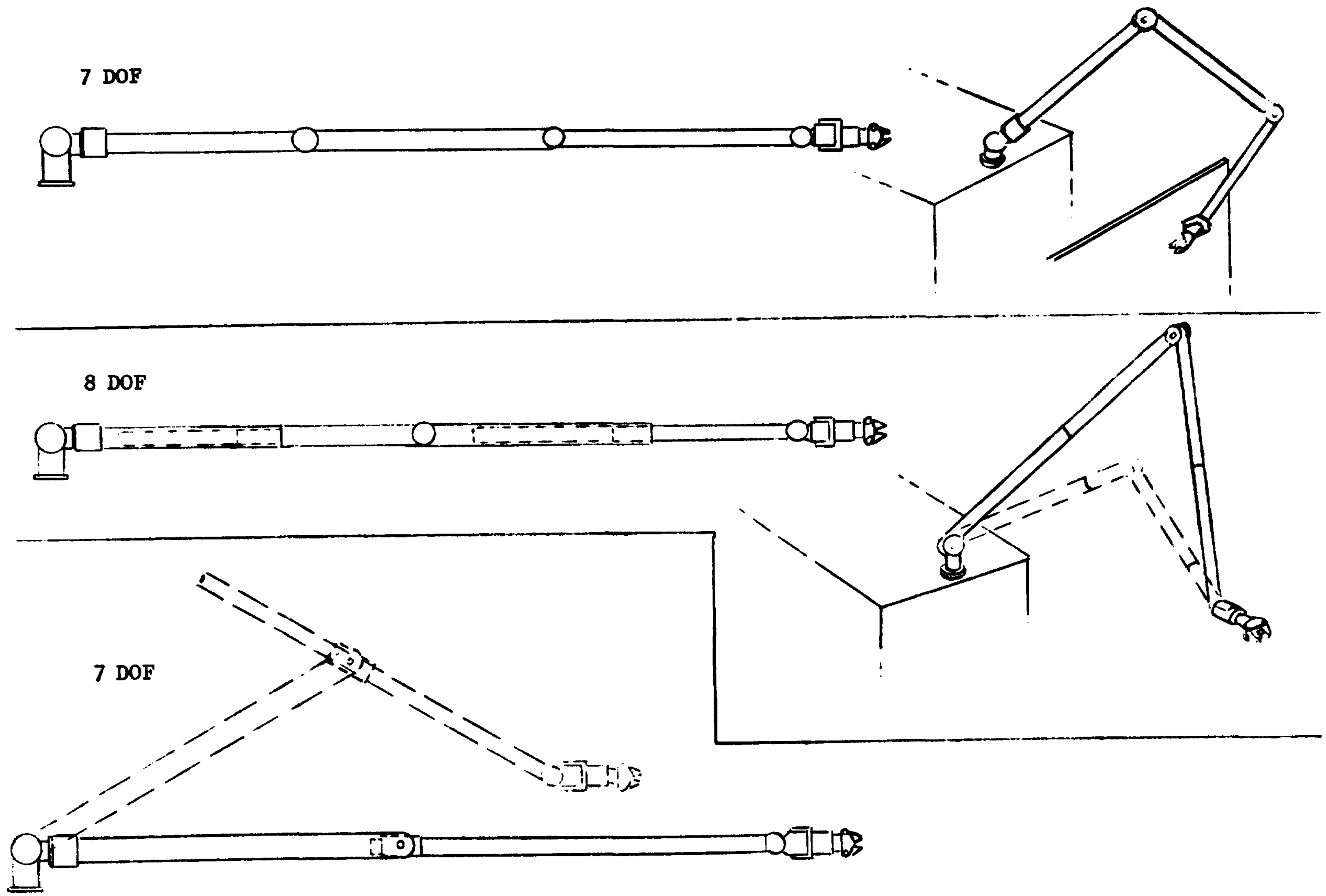


Figure IV-12 More than 6 DOF Manipulator Concepts

4. Retrieval Manipulator Configurations

The Retrieval Manipulator is essentially a special case of the General Purpose Manipulator and the analysis used for the General Purpose Manipulator directly applies to the Retrieval Manipulator. The requirements for the Retrieval Manipulator strongly depends on the satellite dynamic state and the resulting satellite motion after contact (Ref. 4, Task 2 Final Report). Table IV-1 lists manipulator degrees-of-freedom required. For a stable satellite the retrieval manipulator can be as simple as a basic docking device. If the satellite is spinning/tumbling, the most effective location (i.e. longest distance from the center of mass) to apply torques is on the end of a cylindrical body. Thus, the Retrieval Manipulator must be capable of tracking the circular coning and spinning motions.

Preliminary studies (Ref. 6) indicate that if the spinning and coning angular momentum are removed simultaneously, the relative satellite/FFTS position remains the same. In other words, as the angular momentum is being reduced, only the joints which provide circular motion and spin motion must be driven. Reach control is not necessary.

The Retrieval Device can be a simple docking device like that shown in Fig. IV-13 where tne arm can extend, rotate and attach to the satellite. Despin torque is applied to remove the spin momentum.

Table IV-1 Retrieval Manipulator DOF Requirements

Satellite	DOF	Function
Stable	1	Provide Structural Attachment
Spinning	1	Despin Torque
	2	Grip and Structural Attachment
Tumbling	2	At Base-Circular Motion
	1	At Elbow-Reach Control
	1	At Wrist-Interface Alignment
	2	At Wrist-Grip and Struc. Att.
Spinning Tumbling	2	At Base-Circular Motion
	1	At Elbow-Reach Control
	1	At Wrist-Interface Alignment
	1	At Wrist Despin Torque
	2	At Wrist Grip and Struc. Att.

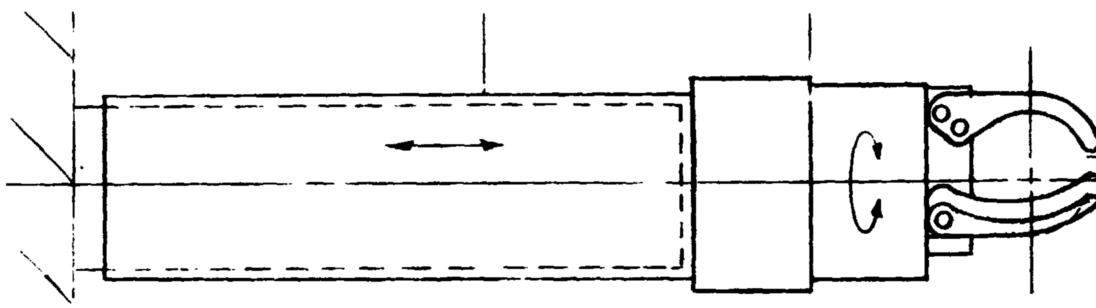


Figure IV-13 Retrieval Device Concept

Fig. IV-14 shows a number of more complex Retrieval Manipulator concepts. The preferred configuration is shown in Fig. IV-15. It has two options depending on the feasibility of building a continuous roll joint at the base of the manipulator. In the continuous roll case, the joint sequence is as follows:

Roll Pitch	Base
Extend or Pitch (Optional)	Elbow
Pitch Roll	Wrist

For the non-continuous roll case the joint sequence is slightly different:

Yaw Pitch	Base
Extend or Pitch	Elbow
Pitch Yaw Roll	Wrist

The additional DOF is required at the wrist due to the motion of the elbow. In the continuous roll configuration, the elbow moves in a circle with the center perpendicular to a line from the base of the manipulator. In the non-continuous roll configuration, the elbow

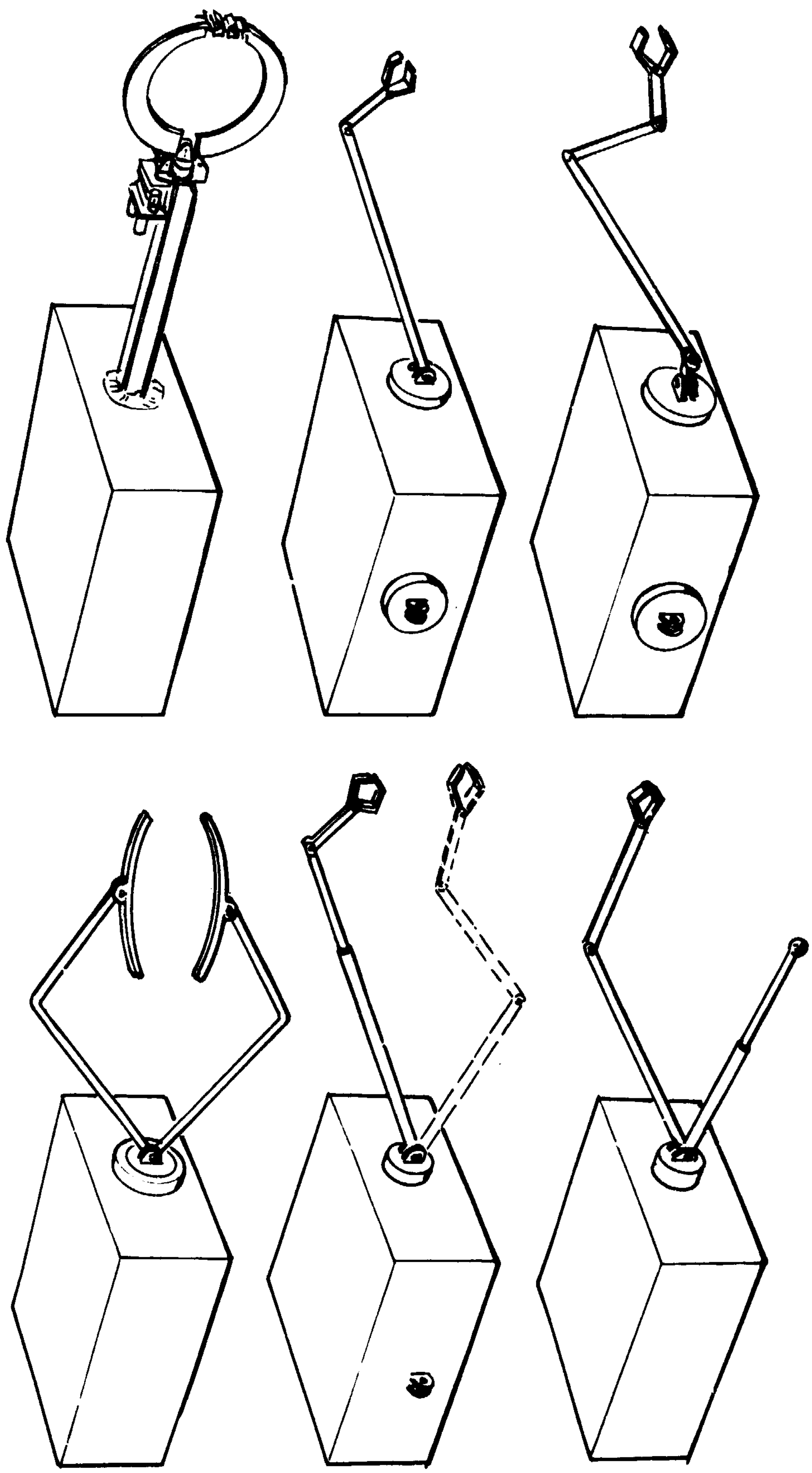


Figure IV-14 Retrieval Manipulator Concepts

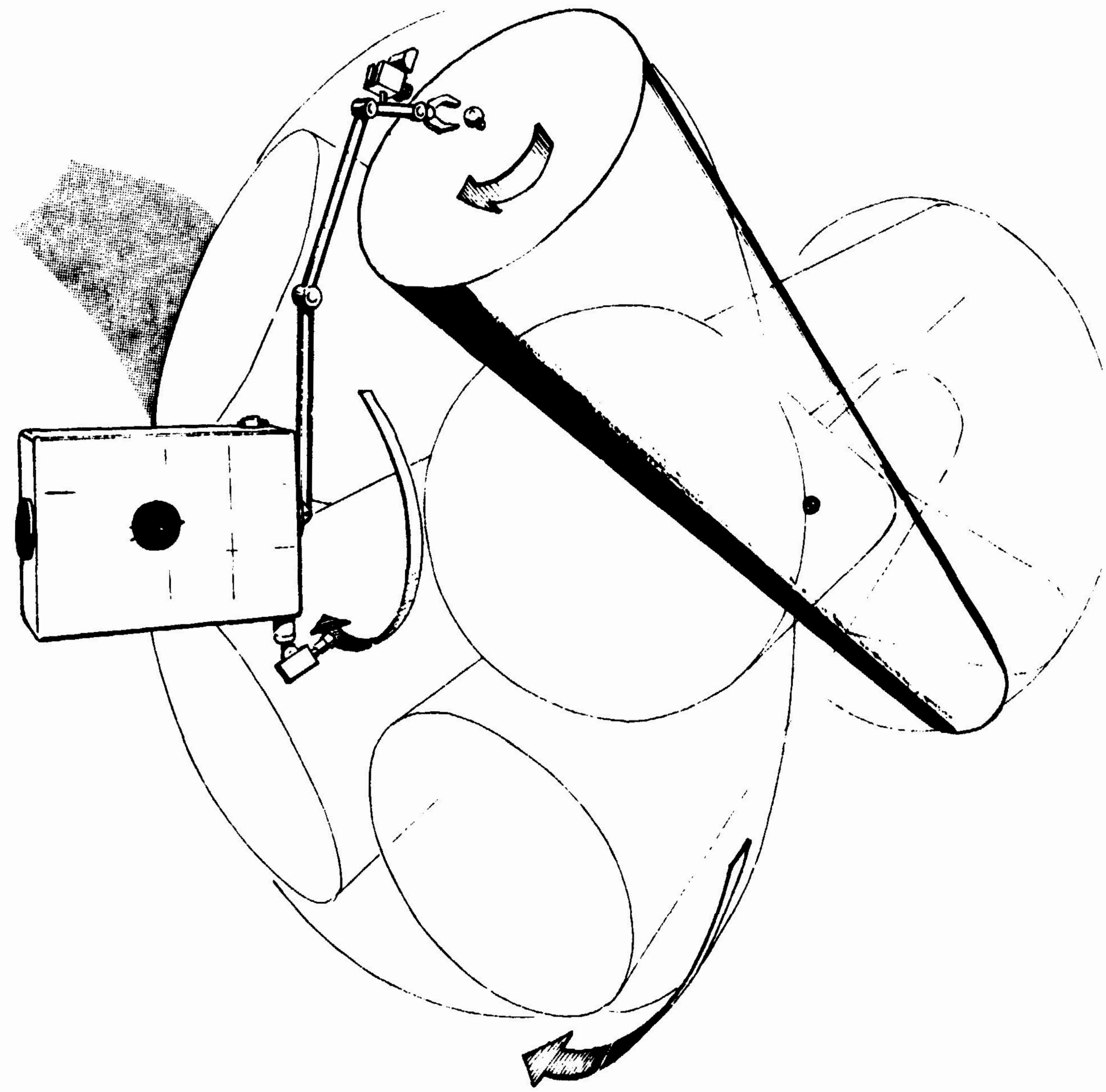


Figure IV-15 Preferred Retrieval Manipulator moves in a circle with a perpendicular line from the center above the base of the manipulator arm. To compensate or track the satellite this configuration requires an additional DOF at the wrist; yaw.

Also, the extension or pitch at the elbow is not required for retrieval provided the arm is of sufficient length for the maximum cone angle. This length can be adjusted by moving the FFTS relative to the satellite. The extension or articulation at the elbow does, however, provide advantages for stowage.

5. Manipulator Configuration Summary

In summary, simple mechanisms that are easily controlled and are generally lighter weight, can provide satellite servicing if constraints are placed on the module/satellite interface, module service/stowage locations, and the satellite module servicing area must be relatively free of obstructions.

On the other hand, if few restraints are to be placed on the satellite designer, a truly General Purpose manipulator requires a minimum of six DOF. The concepts are summarized in Table IV-2.

Table IV-2 General Purpose Manipulator Summary

Configuration	Manipulator Degrees of Freedom	Evaluation
Turret	2	. Recommended for a well prepared FFTS/Satellite Interface
Circular	3	. Simple Easy to control and lightweight
Boom	3	
Cylindrical Coordinates	4	
Cartesian Coordinates	4	
Articulated Manipulator/Docking Device	3-6	. "General Purpose" from an operational Flexibility Standpoint . Has large volume/reach capability
Full Motion Manipulator	6	. More complex from a control standpoint

The Retrieval Manipulator is a special case of the General Purpose Manipulator. As shown in Table IV-3, a Retrieval Manipulator is primarily applicable to retrieval of spinning/coning satellites with high spin rates and large cone angles. Satellites, with other dynamic states may be retrieved using a docking device or the General Purpose Manipulator.

B. CONTROLLERS

Based upon the manipulator system state-of-the-art survey, numerous controller types were identified. These included proven techniques as well as proposed approaches, and included the following:

- SWITCHES
- POTENTIOMETERS
- 3-6 DOF JOYSTICKS
- GEOMETRICALLY SIMILAR
  - MASTER-SLAVE
  - EXOSKELETON
  - REPLICA
- NON-GEOMETRIC
- ISOMETRIC
- TERMINAL POINTER

In general, the controllers are used to control either the position or rate of the manipulator as illustrated in Fig. IV-16. However, one controller, the terminal pointer, is used in a hybrid fashion i.e. controlling the end effector location in a rate mode while the end effector attitude is controlled in a position mode. The controller types were divided into two distinct classes, namely rate and position types.

Table IV-3 Satellite Retrieval Device Application

Satellite State	Retrieval Device	General Purpose Manipulator	Retrieval Type Manipulator
Stable	Primary	Secondary	Alternate
Spin	Primary	Secondary	Alternate
Tumble			
Low Rates	Primary	Secondary	Alternate
High Rates			
Tumble Axis	Primary	Secondary	Alternate
Tumble Plane	N/A	N/A	Primary
Spin/Tumble			
Low Rates (Any Cone Angle)	Primary	N/A	Secondary
Small Cone Angles	N/A	Primary*	Secondary
High Rates (Large Cone Angles)	N/A	N/A	Primary

* Assumes Ability to Track Circular Motion (Cone Rate)

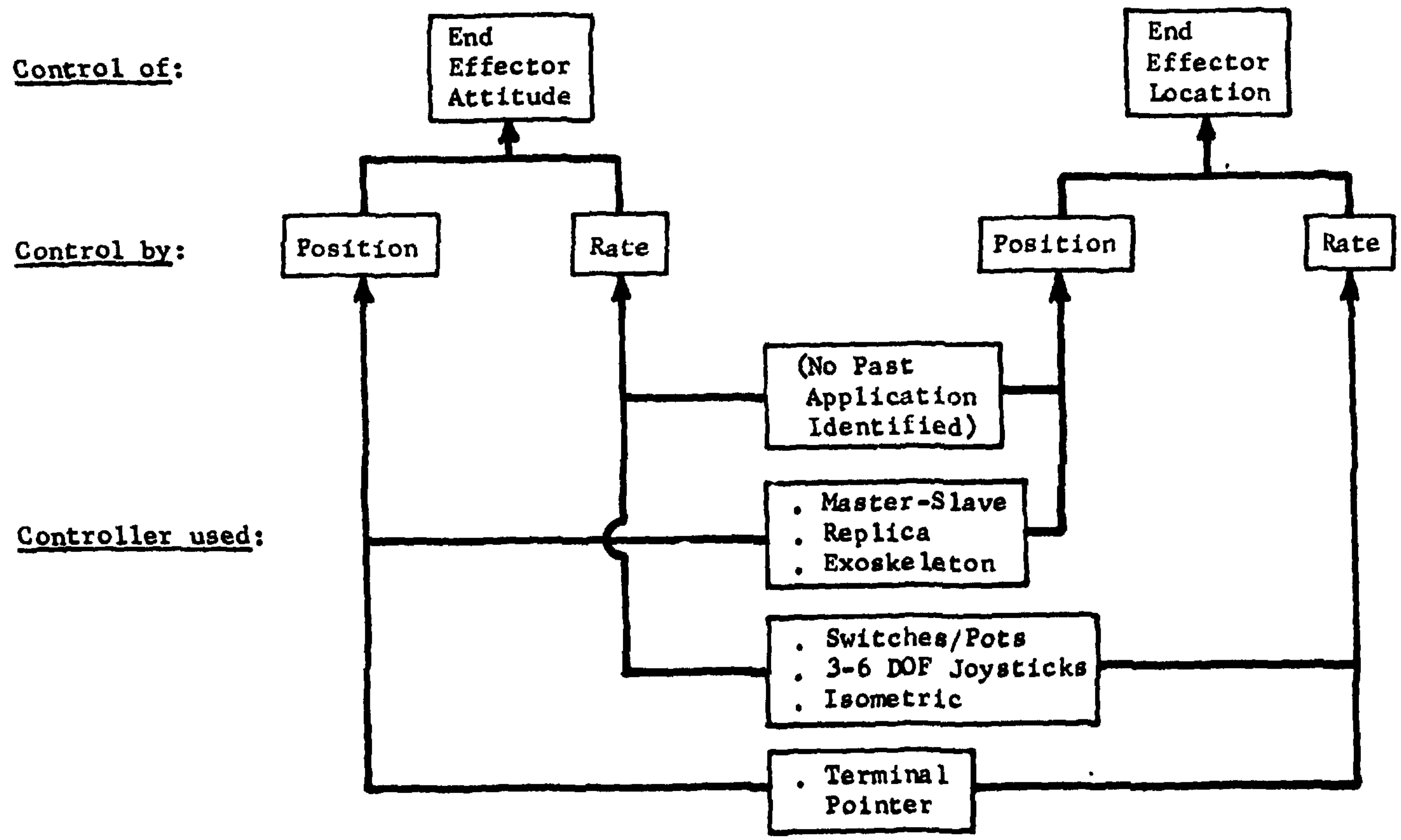


Figure IV-16 Manipulator Controller Methods

1. Rate Type Controllers

Typical rate type controllers are illustrated in Fig. IV-17, with their respective advantages and disadvantages identified. As a generalized summary, the switch/potentiometer types are applicable to limited degree-of-freedom (DOF) manipulator systems or in cases such as spinning (and/or nutating) satellite retrieval where constant rates are required. The choice of 3-6 DOF controllers is primarily based upon operator performance and cross coupling considerations.

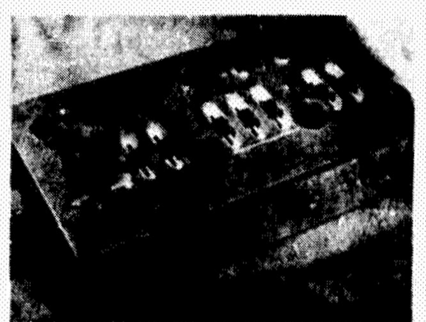
2. Position Type Controllers

Position type controllers generally fall within two classes: geometrically similar and non-geometrically similar or sometimes referred to as replica and non-replica position-position type controllers.

a. Geometrically Similar Position Controllers - The geometrically similar position controllers, shown in Fig. IV-18, include master-slave, replica, and exoskeleton devices. The master-slave type controller is basically a controller identical to the manipulator configuration and inherently incorporates force-feedback (or bilateral control). The exoskeleton controller, whether containing bilateral features or not, is used primarily in cases where the manipulator configuration has essentially "human arm-like" characterististics. The replica controller is simply a full-scale or miniature model of the manipulator such that in its normal use it is connected on a joint-to-joint basis with the manipulator.

However, while the simplicity of these devices from a control point of view is extremely advantageous, from a systems viewpoint these devices may not result in an attractive approach. This is illustrated by Fig. IV-19 in which additional requirements of the manipulator system tend to drive the controller towards a non-geometric or non-replica device. Basically, anytime indexing is required to eliminate awkward operator arm positions, or reference axis changes are required to provide alternate indirect viewing locations, or gain ratios switched to produce increased operator/controller positional sensitivity, the replica

SWITCHES/POTENTIOMETERS



PAR Model 3000 Control Box

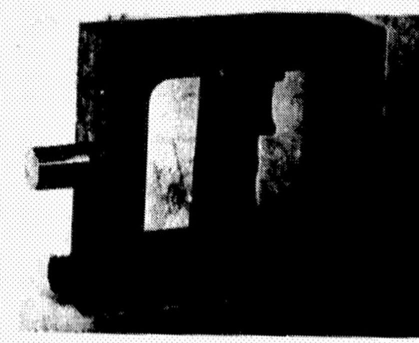
ADVANTAGES:

- Simplicity
- Minimum Volume
- Minimum Control Electronics
- No Cross Coupling

DISADVANTAGES:

- No Force Feedback
- Excessive Operator Workload
- Coordinated Motion Difficult

MIT 6 D.O.F. ISOMETRIC CONTROLLER



ADVANTAGES:

- Small Operating Volume
- Small Input Capability
- Variable Control Gains

DISADVANTAGES:

- Cross-Coupling
- No Force Feedback
- Requires Computational Electronics

MATRIX TERMINAL POINTER HAND CONTROLLER

ADVANTAGES:

- Small Operating Volume
- Directional Feedback
- Minimal Cross Coupling
- Variable Velocity Control Gains

DISADVANTAGES:

- Restricted Tip Motions
- Peculiar Wrist Positions
- Large Computational Requirements
- No Force Feedback

2 - 3 DEGREE-OF-FREEDOM JOYSTICKS

3 DOF Attitude

3 DOF Translation

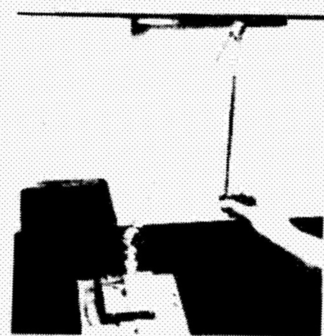
ADVANTAGES:

- Small Operating Volume
- No Cross Coupling
- Small Input Capability
- Variable Control Gains

DISADVANTAGES:

- No Force Feedback
- Requires Computational Electronics

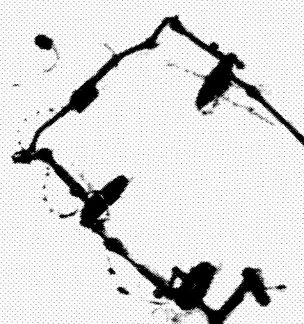
Figure IV-17 Rate Controllers



Replica or Model

ADVANTAGES:

- Minimum Control Electronics
- Provides Position Feedback
- Incorporates Force Feedback



Exoskeleton

DISADVANTAGES:

- Increased Operating Volume
- Cross Coupling
- Limited Indexing Capability
- Human Arm Limitations

Figure IV-18 Geometrically Similar Position Controllers

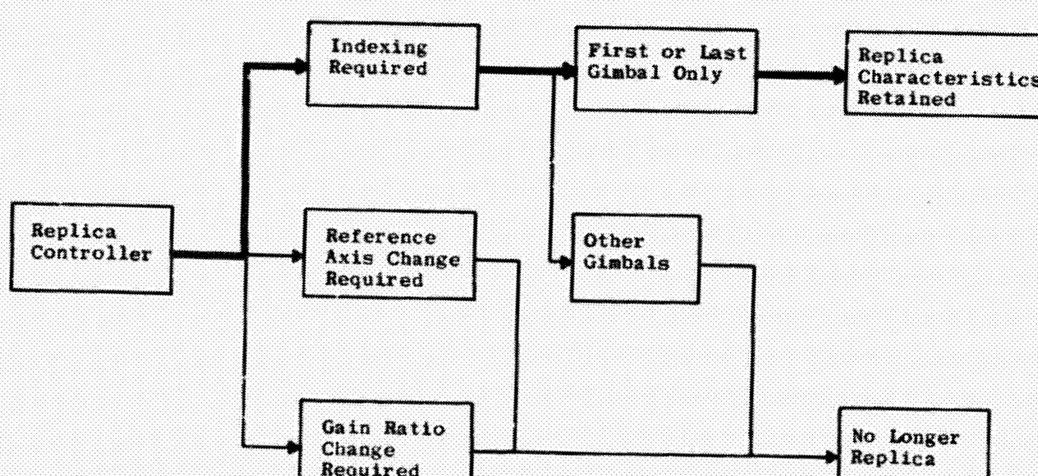


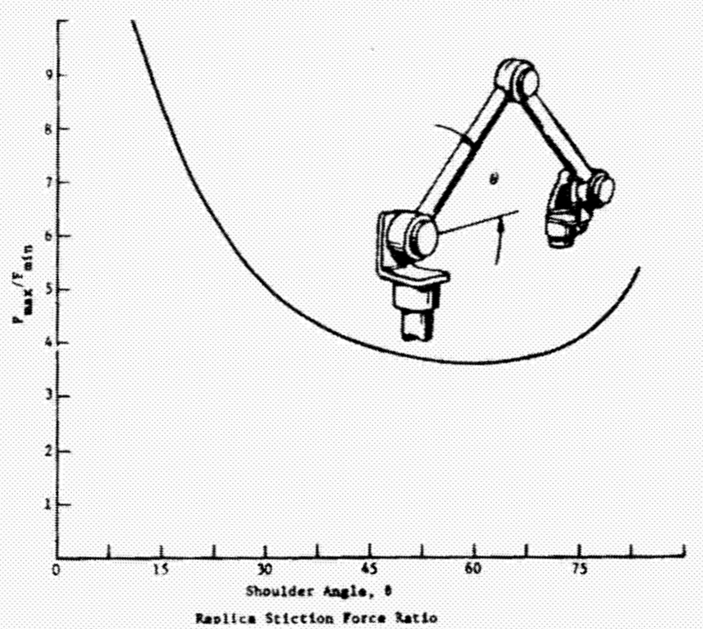
Figure IV-19 Repl:ca Controller Analysis Flow Diagram

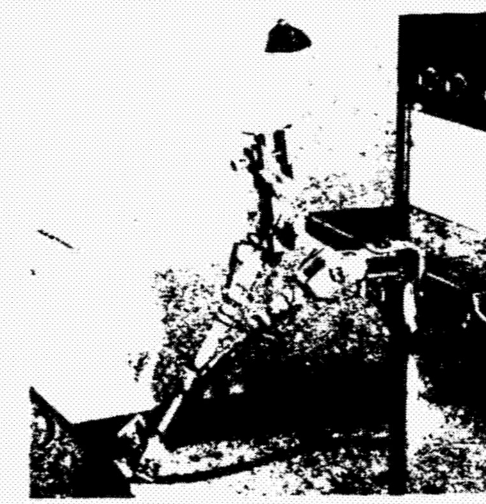
controller characteristics are no longer retained. In general, this will be the case for FFTS applications in which minimum controller volumetric requirements exist. Therefore, strong considerations were given to the non-geometric position type controller concepts.

b. Non-Geometrically Similar Position Controllers - Numerous non-geometrically similar position controller concepts have been evaluated using mock-ups (Ref. 7). As a result of the mock-up evaluations, prototype controllers were constructed and evaluated through man-in-the-loop manipulator simulations. Two of the more promising concepts were the "elbow" and the "sliding base" positional controllers shown in Figs. IV-20 and IV-21.

(1) Elbow Type: The evaluation of this controller concept established several design deficiencies. First, the "stacked" gimbals for attitude control produced cross-coupling between the attitude gimbals and the translational gimbals. The primary reason for stacking the gimbals was to retain similarity to the manipulator wrist gimbals. Secondly, as the elbow angle changes, the force required to backdrive the joints changes significantly. This force relationship, referred to as the "toggle effect", is illustrated in Fig. IV-20. For a force ratio of 4 or less, the angle θ must remain between 45° and 75°, an undesirable restriction. However, if larger angles are used, the backdrive forces increase creating the possibility of the forces being interpreted by the operator as real manipulator tip forces.

(2) Sliding Base: The sliding base controller configuration incorporated attitude control gimbals balanced about the operator's wrist. Translation is provided by a yaw, pitch, and sliding base gimbal arrangement. The primary disadvantage of this concept arose when a large translation offset existed as a result of a Y or Z translational command. This rotated the forward arm of the controller off at some significant angle in relation to the sliding mechanism,





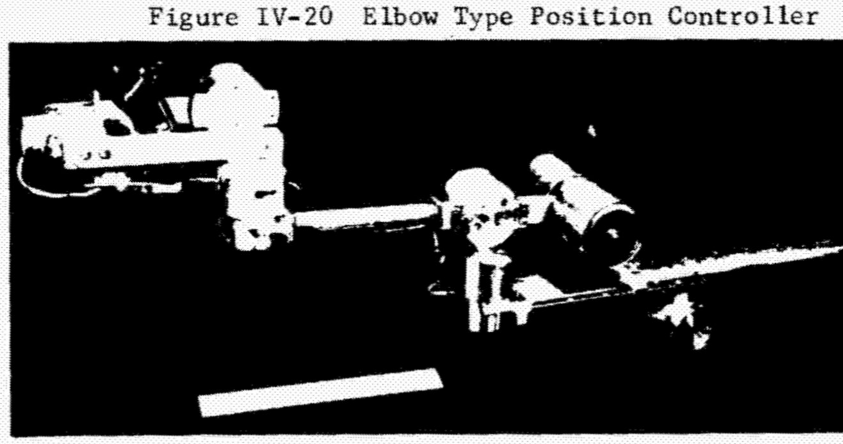
Advantages:

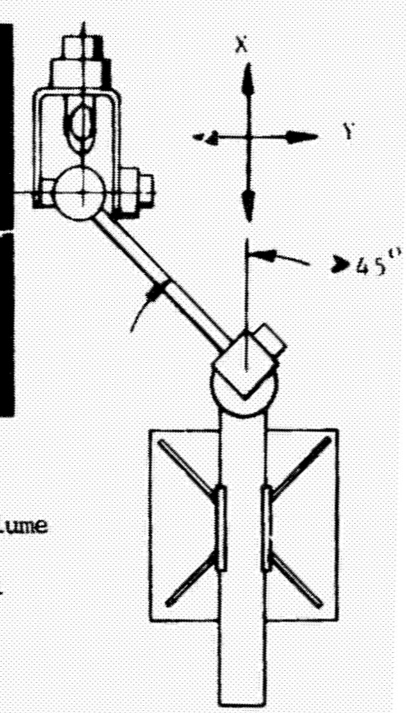
- Retains Replica Characteristics

Disadvantages:

- Cross-Coupling
- Variable Force Ratio
- Gimbal Lock/Singularities

Figure IV-20 Elbow Type Position Controller





Advantages:

- Force Feedback
- Indexing Capability
- Variable Gains

Disadvantages:

- Large Operating Volume
- Cross Coupling
- Large Computational Requirements

Figure IV-21 Sliding Base Position Controller

45 to 60°. Translation in X became difficult to control at, or near, these angles. As can be seen from Fig. IV-21 the control grip has shifted significantly off its plane of travel which, not only creates coupling between X and Y but the force required to position the slider varies with the angle of the upper arm segment. As the angle of the upper arm segment increases, combined X and Y/Z translations become more difficult to command.

(3) Vertical Slider: A third concept, shown in Fig. IV-22 was proposed to eliminate the limitations of the previous concepts. By placing the translational gimbals away from the normal operational volume large angular travel is not required. Thus, large operator force requirements and gimbal lock are avoided.

Advantages:

- Long Length Eliminates Gimbal Lock or Large Angular Travel
- Contains Replica Type Features
- Reduces % Change in Force Feedback/Length

Disadvantages:

- None (with respect to other position controller concepts)

Figure IV-22 Vertical Slider Position Controller

3. Dual Purpose Controllers

Two additional controller concepts were considered during this study. Both concepts were based upon attempts to provide commonality between the FFTS controllers and either the retrieval or general purpose type manipulator systems. While recognizing the potential incompatibility of optimization from an operator feel/performance point of view, the reduction in overall system mass, volume, and cost aspects could not be ignored.

a. Satellite Retrieval - One typical approach, based on the use of Apollo-type or similar controls for the FFTS, is illustrated in Fig. IV-23. The only modification is adding the manipulator length and coning rate control switches to the FFTS attitude controller. As the FFTS must be constantly positioned during a retrieval task, this concept enables a single operator to control both the FFTS and the manipulative functions without removing his hands from one controller to another.

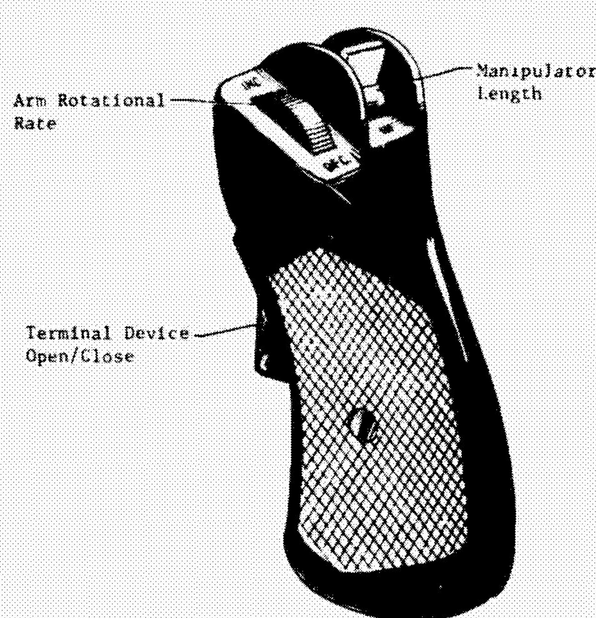


Figure IV-23 Dual-Purpose Apollo-type Control Concept

b. Satellite Maintenance - For maintenance-type applications, assuming the FFTS has docked or is attached at the worksite, the FFTS controls are not in use. Again the possibility exists of using these controllers for translating the manipulator and rotating the wrist gimbal in a rate mode. The present Apollo translational controller has switches and is used in an acceleration mode. However, the switches could provide a constant rate command to the manipulator or, with the addition of pots or resolvers, provide a variable-rate system.

One additional function on the Apollo-type translational controller is a rotary motion for an abort command. This function for manipulative control could provide emergency braking to all manipulator actuators, an automatic stowage command, or end effector grip/release commands.

Another manipulator controller concept considered is essentially the converse of the previous concept. This technique, shown in Fig. IV-24 is based on the use of a position-type controller for the manipulator system. The manipulator wrist attitude controller gimbals are used to control the FFTS attitude. The manipulator commands would be eliminated via a physical locking system and the attitude commands switched to the FFTS control electronics. This approach is primarily applicable to a general purpose manipulator where no simultaneous FFTS and manipulator attitude commands are required.

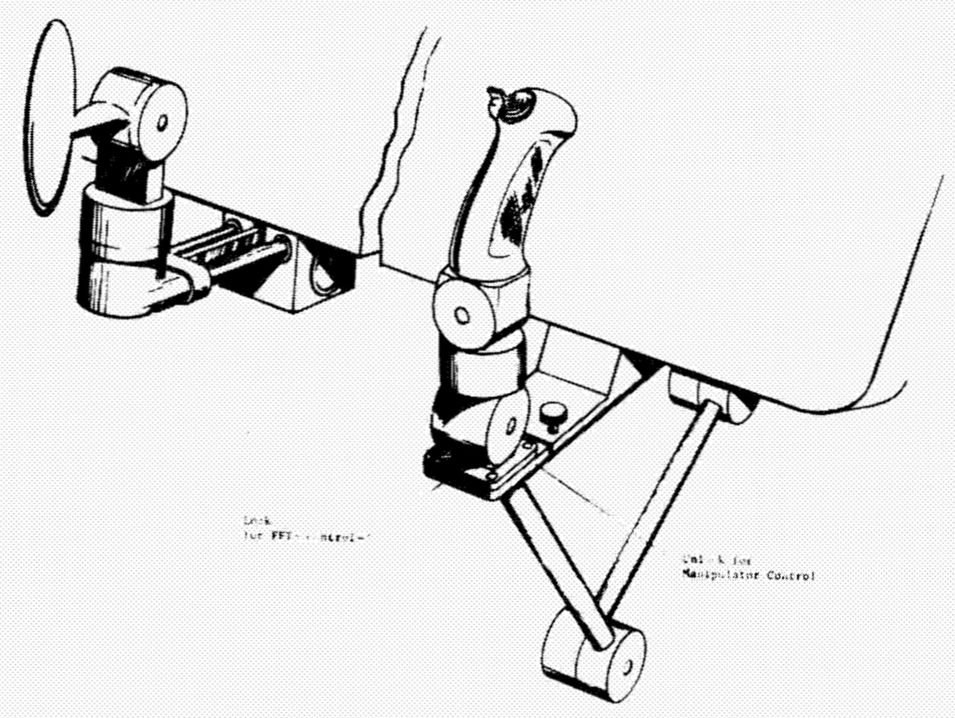


Figure IV-24 Dual-Purpose Position Control Concept

4. Controller Application Summary

The general class of controller concepts were reviewed and ranked on the basis of (1) is the technique proven, (2) if required can force feedback be incorporated, and (3) its applicability to either the general purpose or retrieval type manipulator. The results are summarized in Fig. IV-25 and the recommended controller types, based upon the application are shown in Fig. IV-26.

Control Device	Proven Technique	Force Feedback	Application G.P.*	R.T.*
Switches Potentiometer	Yes	No	Backup	Primary
3 DOF Joysticks	Yes	No	1	N/A
Geometrically Similar	Yes	Yes	3	N/A
Non-Geometric	Essentially	Yes	2	N/A
Exoskeleton	Yes	Yes	6	N/A
Isometric	No	Possible	4	N/A
Terminal Pointer	No	Wrist Only	5	N/A
* G.P. - General Purpose		R.T. - Retrieval Type		

Figure IV-25 Controller Application Summary

<u>General Purpose Manipulator</u>

- No Force Feedback
  - (1) Two 3 DOF Joysticks: 1 Translational; 1 Rotational
  - (2) Non-Geometric Position Controller
- With Force Feedback
  - (1) Non-Geometric Position Controller

<u>Retrieval Type Manipulator</u>

- Switches/Potentiometers
  - (1) Integral with the FFTS Controllers
  - (2) Mounted on the Control Console

Figure IV-26 Controller Recommendations

C. CONTROL MODE CONCEPTS

A "control mode" refers to the type of coupling between the input control device and the manipulator joint drives. Encompassed in a specific control mode are the number and sequencing of the controller and manipulator degrees of freedom, the type of sensing elements (i.e. position, rate, etc.) at each degree of freedom, the type (cartesian, spherical, etc.) and location (base, end effector) of all coordinate systems from which commands are issued and in which the manipulator operates, and all control law equations needed to compute position, rate, torque, and coordinate transformation values.

Many proven and conceptual control modes exist for industrial, hot lab, and space oriented remote manipulators. Of these control techniques, the ones appearing most applicable to the free flyer teleoperator are briefly reviewed. The considered methods range from the extremely simple, yet not so versatile, to the highly complex and dexterous. Rate, position, unilateral and bilateral force reflecting techniques are included in the FFTS control mode candidates.

1. Switch Joint Control

The simplist of the rate control techniques, switch joint control allows the operator to activate each manipulator joint on an individual basis. The control console contains one switch per degree of freedom, with switch engagement commanding a preset gimbal rate. Although no control equations and minimal electronics are required, coordinated tip motion is extremely difficult.

2. Replica Control

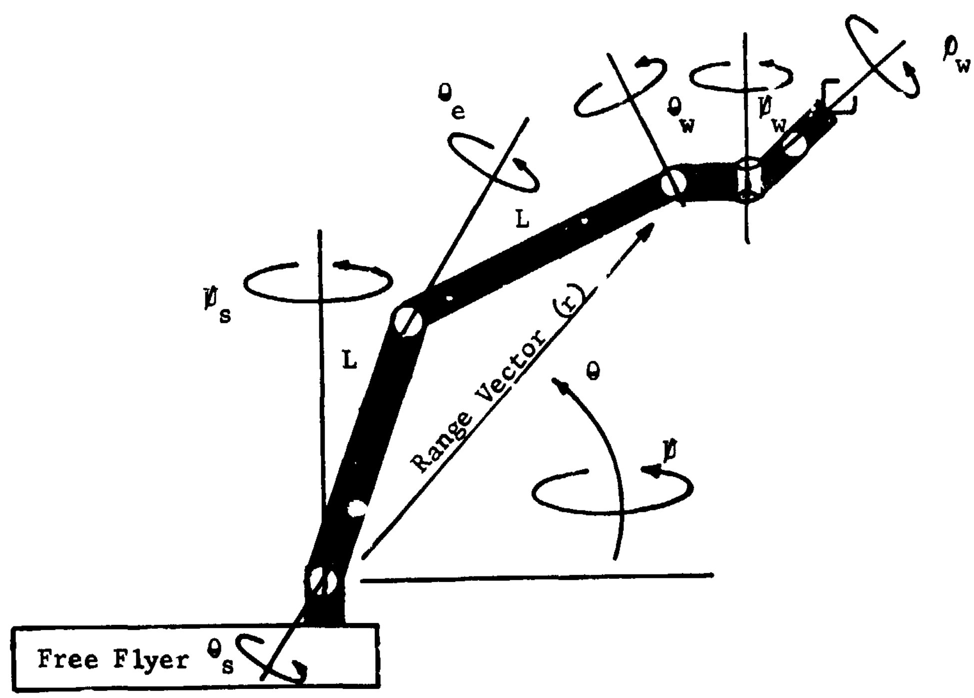
Pioneering master-slave position control, the replica input device contains the same number and ordering of joints as does the manipulator. Each controller joint is connected to, and only to, its counterpart joint on the manipulator, thus providing position correspondence for all gimbal pairs. The replica may be either unilateral or bilateral force reflecting. For bilateral operation, the controller must be powered, and receives its input commands via two way position and/or force information flow The control technique is simple, and when both master and slave can be viewed simultaneously, intricate tasks requiring coordinated motion are easily performed with minimal training time. When control station operating volume is restricted, variable controller-manipulator motion and force reflecting ratios required, and operation in various camera axis desired, the replica controller does not appear to be the optimum choice.

3. Range, Azimuth, Elevation (RAE)/Rotation Control

The simplest of the more sophisticated axis orientated control schemes, RAE/Rotation control utilizes a spherical base coordinate system. Translational and rotational motion are separated in that range, azimuth, and elevation control of the first wrist gimbal attachment point provides translation freedom (Fig. IV-27), with attitude control achieved by coupling the input controller on a one-to-one basis with the three wrist gimbals. Both unilateral rate and bilateral position controllers can be used with the RAE/Rotation technique. Forward, side, and vertical motion of the hand grip correspond to range, azimuth, and elevation commands, respectively, for the position controller.

The simplicity of utilizing spherical coordinates is revealed by the following equations relating gimbal and command degrees of freedom.

1. $r = 2L \text{ (Cosine } \theta_e/2)$ (IV-1)
2. $\theta = \theta_s + \theta_e/2$
3. $\phi = \phi_s$.



1. ϕ_s = shoulder yaw
2. θ_s = shoulder pitch
3. θ_e = elbow pitch
4. θ_w = wrist pitch
5. ϕ_w = wrist yaw
6. ρ_w = wrist roll
7. r = range
8. ϕ = azimuth
9. θ = elevation
10. L = segment length

Figure IV-27 RAE/Rotation Degrees of Freedom

4. X, Y, Z/Rotation Control

Replacing the spherical base coordinates of the above technique with a rectilinear cartesian system, X, Y and Z translation motion of the wrist attachment point is achieved as shown in Figure IV-28.

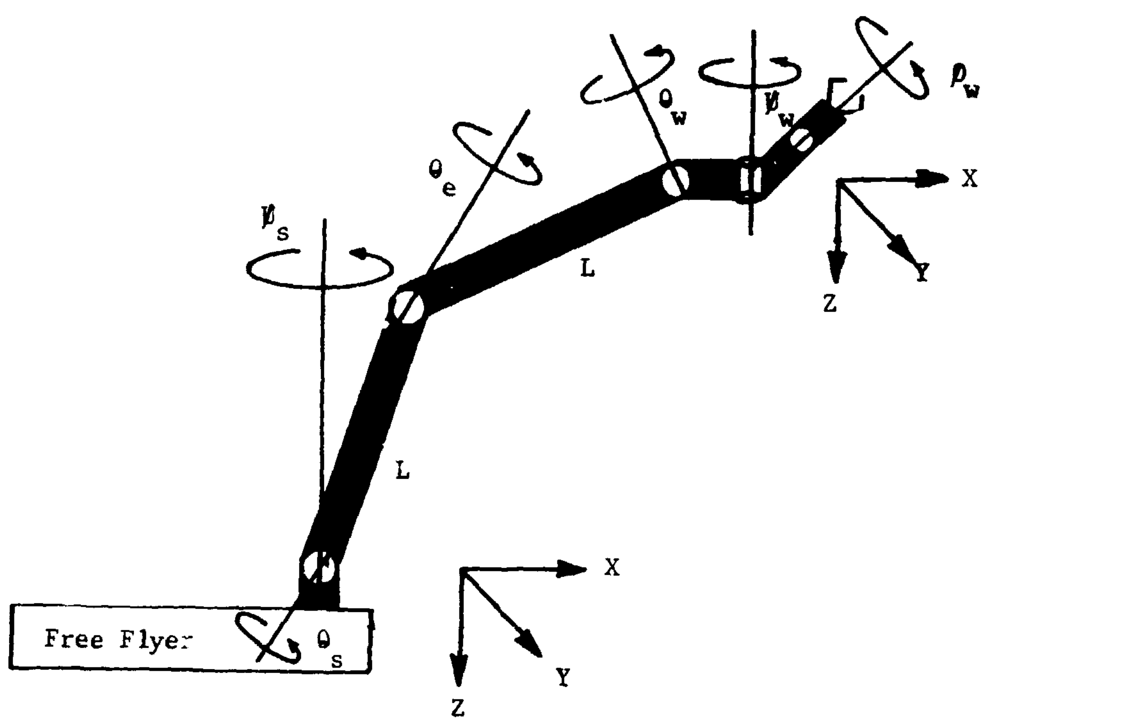


Figure IV-28 XYZ/Rotation Degrees of Freedom

Again, both unilateral rate and bilateral position controllers are applicable for XYZ/Rotation control, with forward, side, and vertical motion of the position controller hand grip corresponding to X, Y, and Z commands, respectively.

Although pure X, Y, and Z straight line motion is achievable with no further transformations (see Appendix E -Simulation Report) the gimbal to command coupling equations become involved as shown by equation IV-2.

$$
\begin{aligned}
&1.\quad X = LC\phi_s\left[C(\theta_s + \theta_e) + C\theta_s\right] \qquad\qquad (IV\text{-}2)\\
&2.\quad Y = LS\phi_s\left[C(\theta_s + \theta_e) + C\theta_s\right]\\
&3.\quad Z = -L\left[S(\theta_s + \theta_e) + S\theta_s\right],
\end{aligned}
$$

where C = Cosine

S = Sine.

5. Resolved Rate Control

Applicable only to unilateral rate controllers, resolved rate control refers to cartesian translational and rotational commanded motion referenced to the terminal device tip, Fig. IV-29.

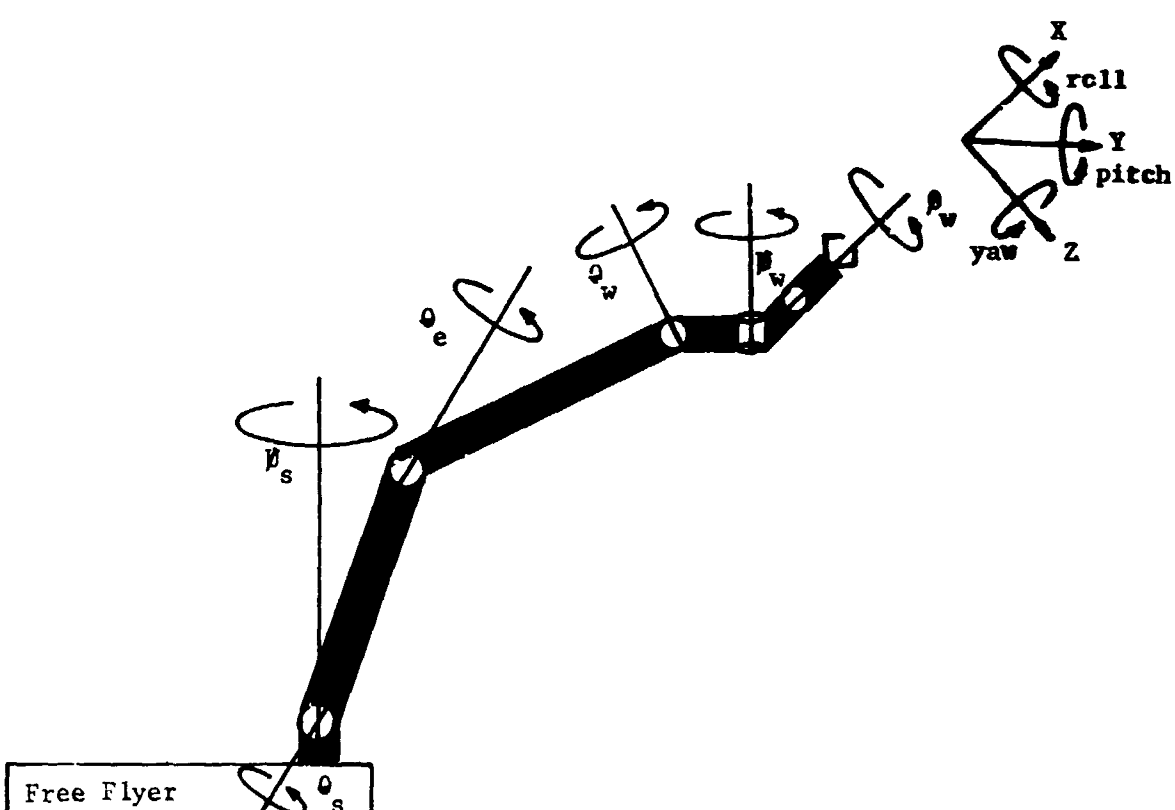


Figure IV-29 Resolved Rate Control

Although a terminal device camera axis system is depicted in the above figure, tip motion commands may be issued in any desired coordinate system.

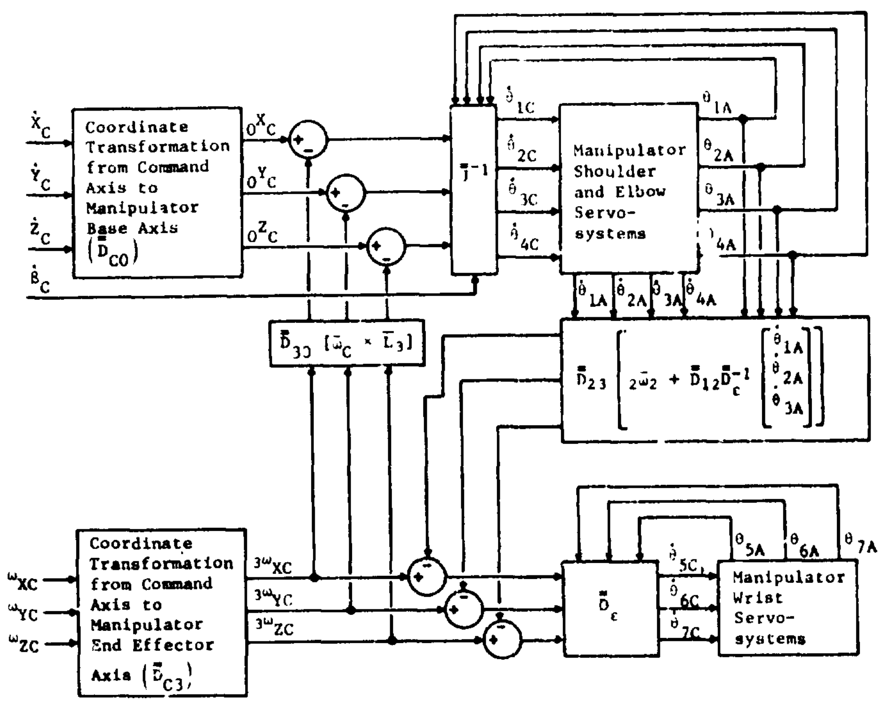
Two proven techniques exist for accomplishing resolved rate control. First, the more straight forward approach derives gimbal commands from the desired tip translational and rotational motion via the six by six Jacobian matrix - the inverse of which must be obtained if joint rate values are needed. The second technique (Fig. IV-30), envisioned by Martin Marietta (report #R72-48664-004) separates translation and attitude computations to produce two-three degree of freedom problems. Although both techniques produce the same end result, the second procedure involves only a three by three matrix inversion, allows input commands to originate from any coordinate system (base camera, end effector camera, etc.), and permits wrist rotation about any selectable point in space.

Resolved Motion Control

In analogy to unilateral resolved rate control, resolved motion refers to a bilateral position controller commanding motion referenced to the terminal device tip. Although all the associated control law equations have yet to be formulated, Fig. IV-31 depicts the nature of the computations and signal channeling required for the translational portion of the problem. By far the most involved of the considered control techniques, resolved motion facilitates: input commands from any axis system, variable and geometry independent force and motion ratios between controller and manipulator, uncoupling of translational and rotational motion, and wrist rotations about any arbitrary point in space.

Inner Loop Force Feedback

Inner loop force feedback (introduced by MIT) is not a complete control mode by itself. It is a control adaptation capable of being used with



Definition of Terms

$\dot{X}_C$, $\dot{Y}_C$, $\dot{Z}_C$ - translation rate commands from any axis system
$\dot{\beta}_C$ - 7-DOF shoulder roll rate command
ω_{XC}, ω_{YC}, ω_{ZC} - rotational rate commands from any axis system
0 - axis system of free-flyer (base)
1 - axis system of manipulator upper arm
2 - axis system of manipulator lower arm
3 - axis system of manipulator end effector
θ_1 - shoulder yaw
θ_2 - shoulder pitch
θ_3 - shoulder roll (7-DOF)
θ_4 - elbow pitch
θ_5 - wrist pitch
θ_6 - wrist yaw
θ_7 - wrist roll
$\bar{\bar{D}}_{ij}$ - coordinate transformation matrix from i^{th} to j^{th} axis system
$\bar{\bar{D}}_\epsilon$ - Euler rate transformation matrix
$\dot{\theta}_{iC}$ - calculated commanded rate of i^{th} joint
θ_{iA} - actual position of i^{th} joint
$\dot{\theta}_{iA}$ - actual rate of i^{th} joint
${}_2\bar{\omega}_2$ - vector containing $\dot{\theta}_{4A}$ as its only nonzero element
$\bar{\bar{J}}$ - Jacobian matrix
$\bar{L}_3$ - vector connecting wrist position to arbitrary point about which rotation is desired

Figure IV-30 Resolved Rate Control Equations

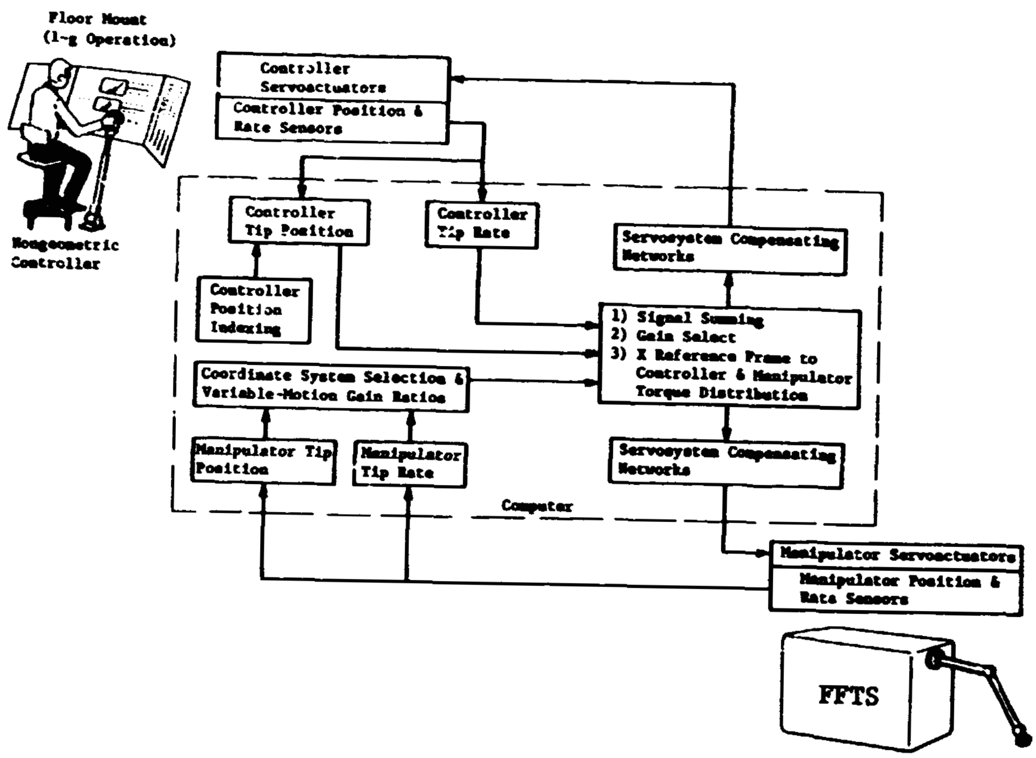


Figure IV-31 Translational Portion of Resolved Motion Control

either a position or rate control input device. Fig. IV-32 depicts the information flow of a teleoperator system containing inner-loop force feedback. Note from the figure that no force information is transmitted back to the operator, but instead is processed by the manipulator electronics and is used in local feedback loops to null all but the commanded forces by the terminal device tip. This technique allows the manipulator to guide itself along a contour or object and can be quite useful when visual feedback is limited or unavailable.

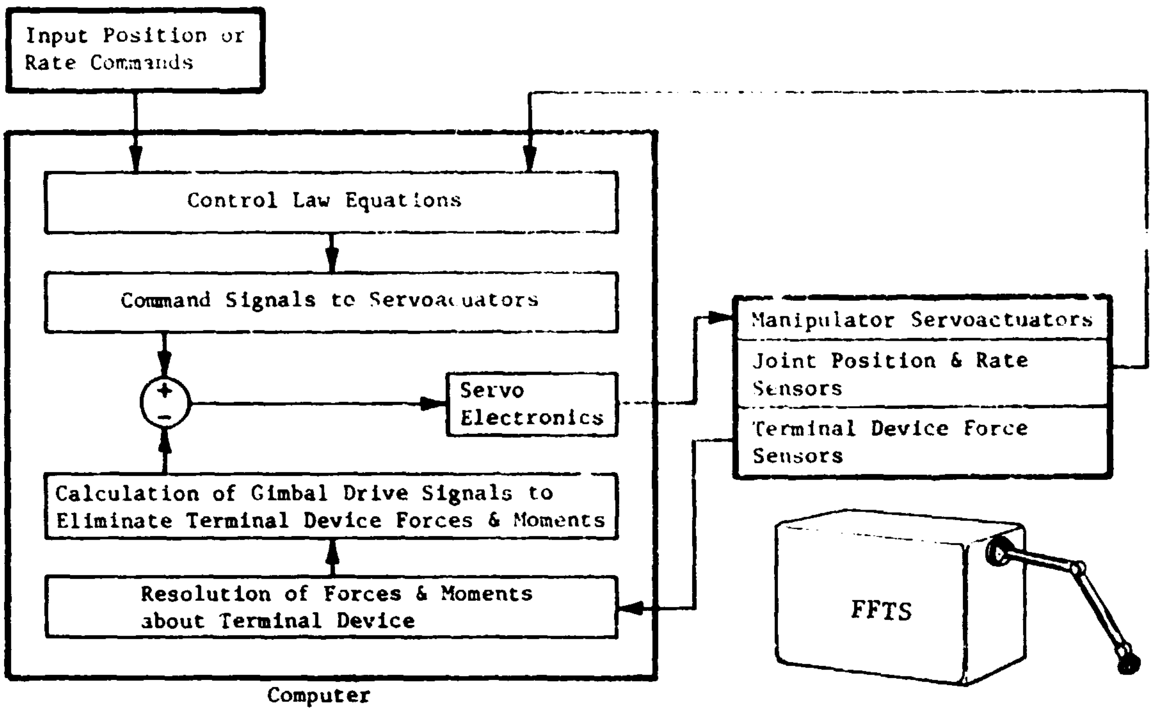


Figure IV-32 Inner Loop Force Feedback

8. Control Mode-System Impact

Table IV-4 relates, in a heuristic manner, the impact of the various control modes on the system parameters:

1. DOF compatibility;
2. Control equation complexity;
3. Actuator components;
4. Time delay effects.

Also included is a summary of the current state of development of each control mode and the applicability of incorporating computer control. The inclusion of automatic control is control mode independent, for the digital computational capability facilitates interfacing with any joint drive technique. Such functions as trajectory generation, pre-programmed trajectories and hazard avoidance (see Martin Marietta report #D-73-48722) are envisioned as possible duties of an on-board computer.

Table IV-4 Control Mode Impact on System Parameters

Control Techniques		Unilateral							Bilateral				Inner Loop Force Feedback	Computer Control
		Proportional Rate			Proportional Position				Proportional Position					
	On-Off Joint	XYZ/ Rotation	RAE/ Rotation	Resolved Rate	Replica	XYZ/ Rotation	RAE/ Rotation	Resolved Motion	Replica	XYZ/ Rotation	RAE/ Rotation	Resolved Motion		
1. Current Evolution														
. Conceptual												✓		
. Experimental		✓		✓		✓		✓		✓			✓	
. Proven	✓		✓		✓		✓		✓		✓			✓
2. DOF Compatibility														
. G.P.* 1-2 DOF	✓				✓				✓					
. G.P. 3-5 DOF	✓	✓	✓		✓	✓	✓		✓	✓	✓			
. G.P. 6 or more	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
. R.T.* Manipulator		✓	✓	✓										
3. Control Equation Complexity														
. None Required	✓				✓				✓					
. Minimal			✓				✓							
. Moderate		✓				✓				✓	✓			
. Complex				✓				✓				✓	✓	✓
4. Actuator Components														
. Position Sensor		✓	**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
. Rate Sensor	✓	✓	✓	✓									✓	✓
5. Time Delay Effects														
. Minimal	✓	✓	✓		✓	✓	✓						✓	✓
. Moderate				✓				✓						
. Severe									✓	✓	✓	✓		

*G.P. = General Purpose Manipulator; R.T. = Retrieval Type Manipulator

**One position sensor needed for basic RAE; four needed for inclusion of Hawk Mode and TD to range vector transformation

The time delay effects, item #5 in above table, on each control mode represent worst conceivable conditions and are obtained by using the educated guess technique. Many of the time delay parameters are yet to be defined and an in depth study of the problem is required. Both servo stability and man-in-the-loop performance were considered when estimating the time delay effects, with worst case conditions being determined by location of the computational electronics (i.e., ground based, shuttle based, on-board free flyer, etc.).

9. Control Mode Selected for Preliminary Design

Based upon a complexity-versatility tradeoff and the knowledge gained from the SMA simulation, the RAE/Rotation control scheme is selected for the free flyer manipulator preliminary design. With incorporation of the full hawk and terminal device to range vector transformation equations, all the capability of the XYZ/Rotation method are achieved yet the control equations are considerably less complex. For a nine foot manipulator, the SMA simulation initial results reveal that: 1) base camera viewing with zoom capability is sufficient, 2) control separation of translational and rotational motion adequate, and 3) tip rotation about an arbitrary point in space unnecessary - thus the versatility, and consequently the complexity, of the resolved rate technique is not required. As for the bilateral-unilateral tradeoff, the SMA simulation also showed that the Martin Marietta conceived implementation of the RAE/Rotation control mode facilitates two important features that allow unilateral rate control to perform tasks initially believed achievable only with a bilateral force reflecting system. First, forces and moments applied by the manipulator tip are accessible from the control law equations, and thus can be visually displayed to the operator. Second, when performing a task normally requiring simultaneous control inputs (turning a rank or opening a door) various gimbals can be completely or partially deactivated to "go-along-for-the-ride" while the task is completed with one, or possibly two, degrees of freedom only. To illustrate, a probereceptical mating is easily accomplished from large initial attitude errors by disengaging the wrist gimbals and giving a forward translational command. Once the probe is initially started, the attitude gimbals easily backdrive to self align, permitting the probe to fully insert with no extraneous forces or moments being developed.

No inner loop force feedback is included in the design, for the belief is held that the visual TV coverage is sufficient for completing all presently invisioned tasks. Likewise, no computer control programs have been developed for it appears that man-in-the-loop can accomplish all foreseen assignments. If further study reveals that a "watch over" (hazard avoidance) or stored trajectory capability is needed, computer commands can be easily interfaced with the RAE base spherical coordinate system.

D. END EFFECTOR

The development of an end effector greatly depends on its functional and physical interfaces. Since neither of these interfaces have been clearly defined for space applications, the first work effort was an attempt to show system impacts. Figure IV-33 presents the logic flow approach used in developing the potential system interactions necessary to derive these interfaces.

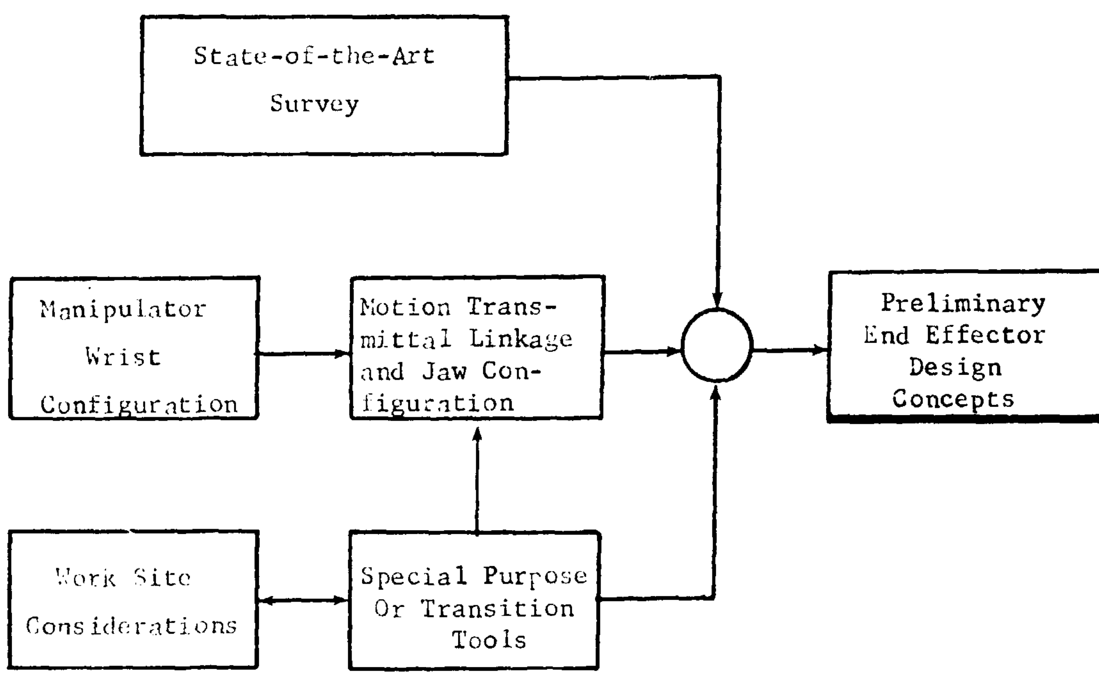


Figure IV-33 End Effector Mechanical Interface Summary

The term end effector, as used in this study, identifies the element on the working end of a manipulator device which performs the basic functions of engage/hold/release. Other terms have been used in the literature reviewed, such as terminal device, grappler, etc. However, for this study, all have assumed the same meaning. In general, the end effector includes all the hardware which functions as the physical mobility link between the last manipulator wrist joint and desired payload task. The actual hardware may take on the physical configuration of a terminal service tool, a transition device or capture tongs. Designing such devices requires both a working knowledge of the desired mission functions, payload tasks, and activity elements and the performance capability associated with the end effector/wrist/arm/vehicle/operator mobility combinations.

The design of the manipulator arm is of interest to this end effector study due to its tip positioning capabilities. It is realized that the greater accuracy or dexterity required of an end effector, the more similar the manipulator movements must match those of the human hand and arm. In turn, as the similarity to human hand and arm movements increases, so does the development cost. Present day space funding doesn't permit the development of a terminal device dexterous enough to simulate the actual human hand control of general commercial hand tools proficiently. However, present technology in the area of on-orbit satellite servicing does not indicate the need for a highly dexterous end effector.

The force and reach requirements for a space manipulator comes primarily from vehicle and cargo sizes, inertias, relative velocities, and vehicle propulsion forces. As identified from previous studies (Ref. 8) where on-orbit satellite servicing is the prime function of the general purpose manipulator, it appears appropriate to design the manipulators to meet human factors, compatible with servicing and assembly-type task and to adjust velocities to stay within the manipulator's design capabilities associated with system optimization. Velocities may be low in relation to operator capabilities. Additional studies and simulations must be performed to establish minimum velocities delegated to different tasks. Until this information becomes available, it is assumed for this trade study that the time factor required to complete a task has a lower priority than system optimization.

The first item of interest was a State-of-the-Art survey which identified many system level requirements applicable to end effector development. It was determined that a general purpose manipulator can be developed that will meet minimum requirements anticipated for most of the proposed missions. Basic system factors used to develop end effector concepts were selected and justified during Task 1 and Task 2. Specific items applicable to end effector design have been identified as follows:

- Electric, motor-driven actuators will be provided at each manipulator degree-of-freedom
- The force capability will be adequate to operate astronaut "hand" tools. This force capability is estimated to be 15 pounds.
- Indirect viewing, such as TV will be used to close the separation distance between the manipulator and control station.
- Anthropometric relationship between hand to end effector and eye to TV will be used in the design to utilize an operator's natural and learned responses.
- Design for universal use of the end effector with many of the anticipated manipulator tasks.
- Task speed will be sacrificed within reason to reduce system weight and complexity.

To summarize, the universal end effector should be interchangeable with the general purpose manipulator and designed to follow the same work procedures and dexterity required of an extravehicular astronaut. This requires the capability to utilize the same tools used by an astronaut. Also, the more specialized the task, the more foresighted the designer must be. However, if the task is too specialized, it may not be economical to provide maintainability through the use of manipulators. The point at which manipulator specialization may become too costly is yet to be determined. To do this, many factors must be considered and trade-offs conducted. Some of the areas effecting the development of universal type end effectors have been evaluated.

Some of the most critical areas which impose requirements are shown in Figure IV-34. Four major areas identified and evaluated were: wrist assembly, worksite, tools, and sensors. Design impacts and preliminary analyses associated with these areas have been discussed in the following paragraphs.

1. Wrist Considerations

The wrist, as defined for this study, includes the hardware that forms the physical transition link between manipulator arm and end effector. The wrist is considered a primary arm section and provides three degrees of freedom: yaw, pitch and roll. The operating parameters can be defined from requirements analysis (tip speed, force, accuracy, etc.) of which a large number of the detailed design parameters are configuration dependent and can be identified from task and related performance analysis. Table IV-5 identifies typical operating characteristics with which the wrist will be capable of providing to the wrist/end effector interfaces.

The most significant requirement is the continuous roll capability and its impacts on the electrical interface design of the end effector (control, sensors, etc.). The present design consideration assumes that there will be no electric hardwire through the wrist/end effector interface.

Table IV-5 Performance Characteristics of Wrist Joints

Joints	Travel Limits rad (deg)	Nominal Speed rad/sec	(deg/sec)	Torque N - m	(ft - lb)	Reversible
Pitch	≥ 1.6 (≥ 90)	0.2	(11.5)	20	(15)	√
Yaw	± 1.5 (± 85)	0.2	(11.5)	20	(15)	√
Roll	Continuous	0.2	(11.5)	20	(15)	√

2. Payload Worksite Considerations

Functional requirements for a manipulator system as a space tool are deter-

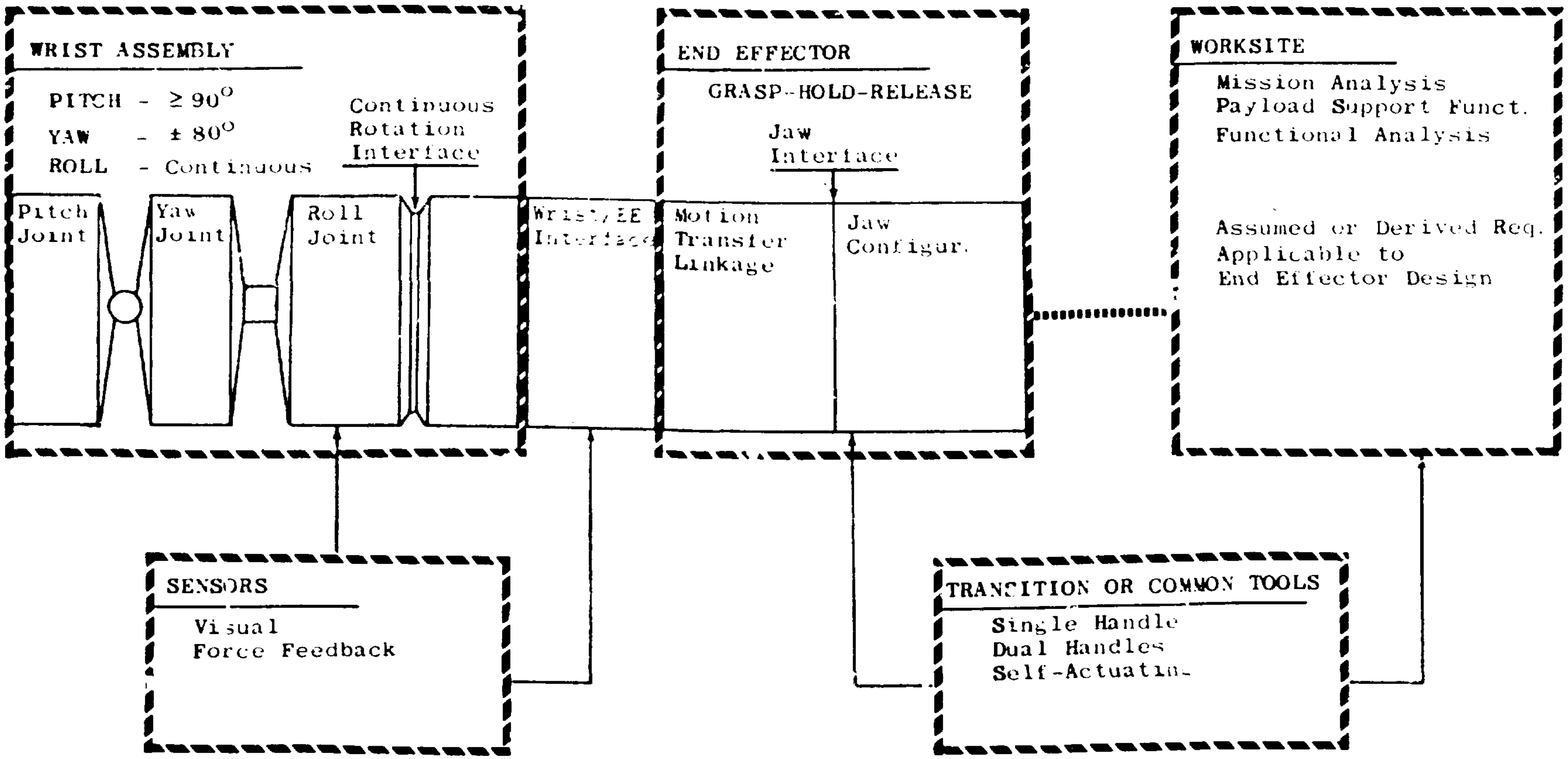


Figure IV-34 Block Schematic of Prime End Effector Interfaces mined by a step-by-step analysis of each work element in each mission task. The study began by examining planned missions as defined in the NASA Shuttle Missions Model (Ref. 9) and correlating common servicing task between missions.

For this study, all areas providing potential payload support were reduced through simplified grouping into five basic areas: payload inspection, payload deploy, payload retrieval, payload servicing and astronaut assistance. Of these, payload servicing was selected for a more detailed analysis due to the many tasks and work elements involved.

Tasks associated with many missions were identified and examined for their common work elements. Most work elements could be grouped as to specific motions required. Typical payload servicing tasks were selected along with their related work elements. These work elements represented the major foreseen servicing tasks and have been listed in Figure IV-35. This list provided the scope of service functions to develop manipulator servicing concepts. The complexity and dexterity levels increased as each prime task was satisfied in going from monitor/inspect through repair. Study results found that even work elements were not well enough defined to determine a level of effort, precision or standardization criteria for a special end effector and tools that could be established for a specific mission. However, Table IV-6 was prepared to show a "first cut" summary of manipulator-oriented activities in the order of their priority.

In order to understand the worksite, one must also understand the meaning of work elements. Work elements are the subdivisions of tasks and, as such, describe the individual requirements. This involves the manipulation or TV system needed to perform a task. Since all servicing is fundamentally a positioning operation, the work elements are broken into classes describing the requirement to move from one position to another. The "capture", "transport", and "place" are fundamental in all work elements and states the class of motion required. For example, some of the terms

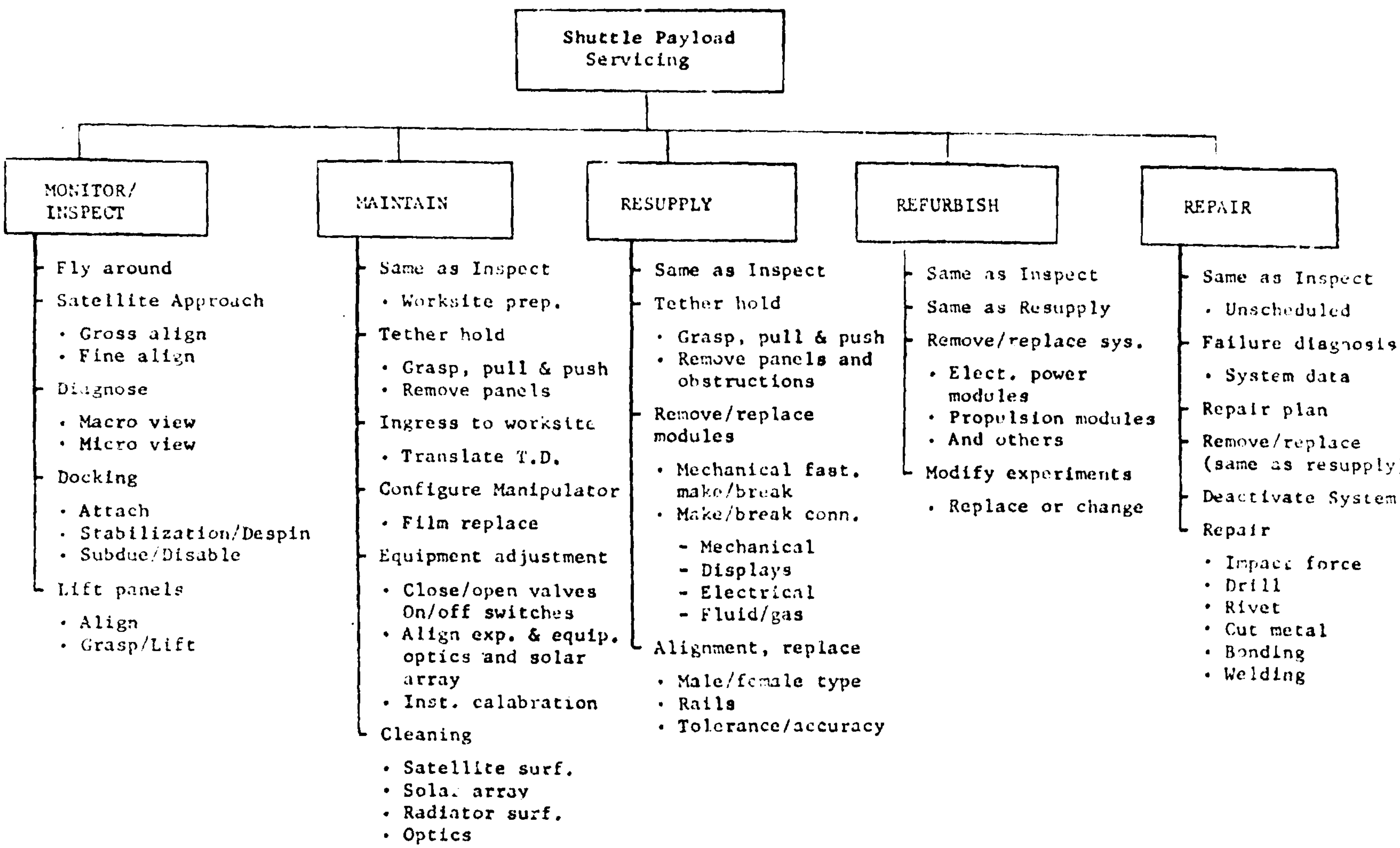


Figure IV-35 Satellite Servicing Functions and Activity Elements

Table IV-6 Summary of Work Task Priority

Work Elements
Positioning
Gross
Fine
Tethering
Remove/Replace Modules
Large Mass Handling
Small Mass Handling
Remove/Install Attachment Fasteners
Captive Cam Type
Captive Screw Type
Adjustment (Valve Handle & Switch)
Hatch Opening
Make/Break Line Connections
Mechanical
Electrical
Fluids
Repair or Assembly
Cutting
Bonding
Welding
Tolerance Checks

used to express work elements are translate, push, pull, up, down, left, right, rotate, grip, etc. The initial and primary reference activity element used in design considerations was the basic remove/replace modules. The worksite interface associated with these activity elements becomes one of the most critical design drivers in developing compatible/low cost end effectors. Any module removed and replaced has positioning, translation, and fastening problems. Some of these problems can be reduced in complexity through standardization, special purpose tools, sensors and aligament aids.

Worksite configuration is impacted by module geometry. Module size has been baselined (Ref. 4) for this study at 150 kg (330 lb) and a dimension of 1 x 1 x 1 m (3.3 x 3.3 x 3.3 ft.). Other considerations include module location, removal method, attachments, lighting conditions and alignment aids.

Fasteners and connectors are involved in many maintenance and assembly tasks. They also take on greater importance as more total time will be used in handling fasteners than in handling any other item. One way to simplify the remove and replace operation is through standarization. Standardization of fasteners for attaching modules can reduce costs considerably; it not only reduces paper work, but also reduces the number of designs, qualification programs and spares, and simplifies inventory and quality control. The standardization of module fasteners would include standardizing on type and size. For example, use either coarse or fine threads; coarse threads are stronger, less subject to thread nicking and more adapted to plating or coating processes. On the other hand, fine threads when used as a gear driver, gi - finer control and greater mechanical advantages. Standardizing faste sizes and strengths reduces the number of fastener types needed and the possibility of installing the wrong fastener. Assembly torque could be standarized to avoid over and under torquing which would result in the need of a single manipulator torque tool for all module remove/replace attachments. Finishes could also be standarized and classified to quality for both primary and secondary application requirements.

The prime program driver, in the area of worksite standarization, yet to be clarified, is the level and to which of these two - the manipulator system or payload worksite - will be permitted to direct the interface design.

3. Tools

The use of transition tools (or general purpose tools) for payload servicing was considered next for compatibility in designing an end effector. The transitional or special purpose tools considered for space applications included the group of common hand tools that could be held within or mounted on the end effector. The choice of tools selected were from the list generated in Table IV-7. Using this list, a comparative matrix was prepared to show the type of motion elements that were required in their normal operation. The actuations required to operate these tools can be provided by the end effector/wrist, or by the manipulator arm articulation.

Since the primary manipulator system was assumed to have force articulations capable of linear travel, rotation, tilt and combinations of these, the other human senses such as viewing, positioning, and temperature were not considered for this comparison analysis. The related force articulations were reduced to a lower level:

- Linear Travel - Combined joint motion
  - Short Strokes (Slow to Fast)
  - Medium Strokes (Slow to Fast)
  - Long Strokes (Slow to Fast)
- Rotation - Wrist roll joint motion
  - Partial, 60° (Slow to Fast)
  - Continuous (Slow to Fast)
- Rotation with Linear Travel - Combination of above (Screw Thread)
  - Partial with Travel (Slow to Fast)
  - Continuous with Travel (Slow to Fast)
- Tilt (Hinge Motion) - Yaw or Pitch motion
  - Travel Arc (0° to TBD)
- Tilt, Bending and Linear Travel - Combination of all joints
  - Short Strokes (Slow to Fast)
  - Medium Strokes (Slow to Fast)

Table IV-7 Potential Actuations to Operate Special or Transition Tools

GENERAL PURPOSE TOOLS	Rotating				Rot. Ins. & Withdrawl				Lineal Travel				Reciprocating Act.				Bending & Lineal			
	Part(60°)		Continuous		Part. (60°)		Contin.		Short		Medium		Short		Medium		Short		Medium	
	Slo	Fst	Slo	Fst	Slo	Fst	Slo	Fst	Slo	Fst	Slo	Fst	Slo	Fst	Slo	Fst	Slo	Fst	Slo	Fst
Exten Bar									Ext Bar		Ext Bar						Ext Bar			
Ratchet Head	Rat Head				Rat Head															
Hammer	Hammer								Hammer				Hammer				Hammer			
Cutters (Wire)	Cutters								Cutter				Cutter							
Cutters (Metal)	Cutters								Cutter				Cutter							
Drill			Drill				Drill													
Rivet									Rivet					Rivet						
Grinder			Grind				Grind		Grind						Grind					
Pry Bar	Pry Bar								Pry Bar								Pry Bar			
Alignment Tool									Alignment Tool											
Box End Wrench					Box Wrench															
Open End Wrench	Open End				Open End															
Off-Set Tool									Off-Set Tool											
Measure									Measure Length											
Screw Driver	Screw Thread				Screw Thread															
Inspt Mirror	Inspt Mirror								Inspt Mirror								Inspt Mirror			
Inspt Light	Inspt Light								Inspt Light											
Welder	Weld		Weld						Weld											
Valve Handle	Val Hand				Val Hand				Val Hand											
Sweeper			Sweeper				Sweeper													

These parameters were compared on an intuitive basis for motions applicable to the operation of each tool. Results of this comparison indicates an end effector having the following actuations will provide adequate tool operating capabilities: (1) linear travel with a medium stroke and slow to medium speed, (2) insert and withdrawal, with continous rotation and variable speed, and (3) high roll torque at stall or low speed at rated torque and high speed at low load.

Torque requirements play an important part in defining worksite configurations relating to fastener and connector shapes, motion envelopes, and tool types required to translate applied torque from the end effector to the worksite. Typical torque requirements for screw threads as shown in Figure IV-36 indicate a common wrench tool would be adequate to achieve the seating torques needed for ¼ inch or smaller bolts. However, as the bolts decrease in size from ¼ inch and down, the task difficulty of align and screw start considerably increases. Also, bolts and nuts do have an increase torque variable in that on repeated use, they have the added problem of corrosion, galling, vacuum welding and cross threading. This difficulty results in two basic options: remove by cutting and replace by special tool that both drills and taps for screws or use a lock pin approach which uses a detent or cam lock technique.

Shape and size of the bolt head or capture hardware must also be considered. Two prime options considered were an external grip and an internal grip. The external grip is common to both bolts and nuts where grasping the head with the parallel jaws is applicable to starting and running bolts and nuts with low torques. This torque limitation is due to either give in the resilient material used on the gripping surfaces or the slop in the end effector gearing device. Hard faced jaws with serrated surfaces may also be used; however, they have the inherent disadvantage of potentially rounding the head through slippage. Head shape for the external grip may be anywhere from a four point to a 12 point socket configuration. Both have advantages and disadvantages, for example,

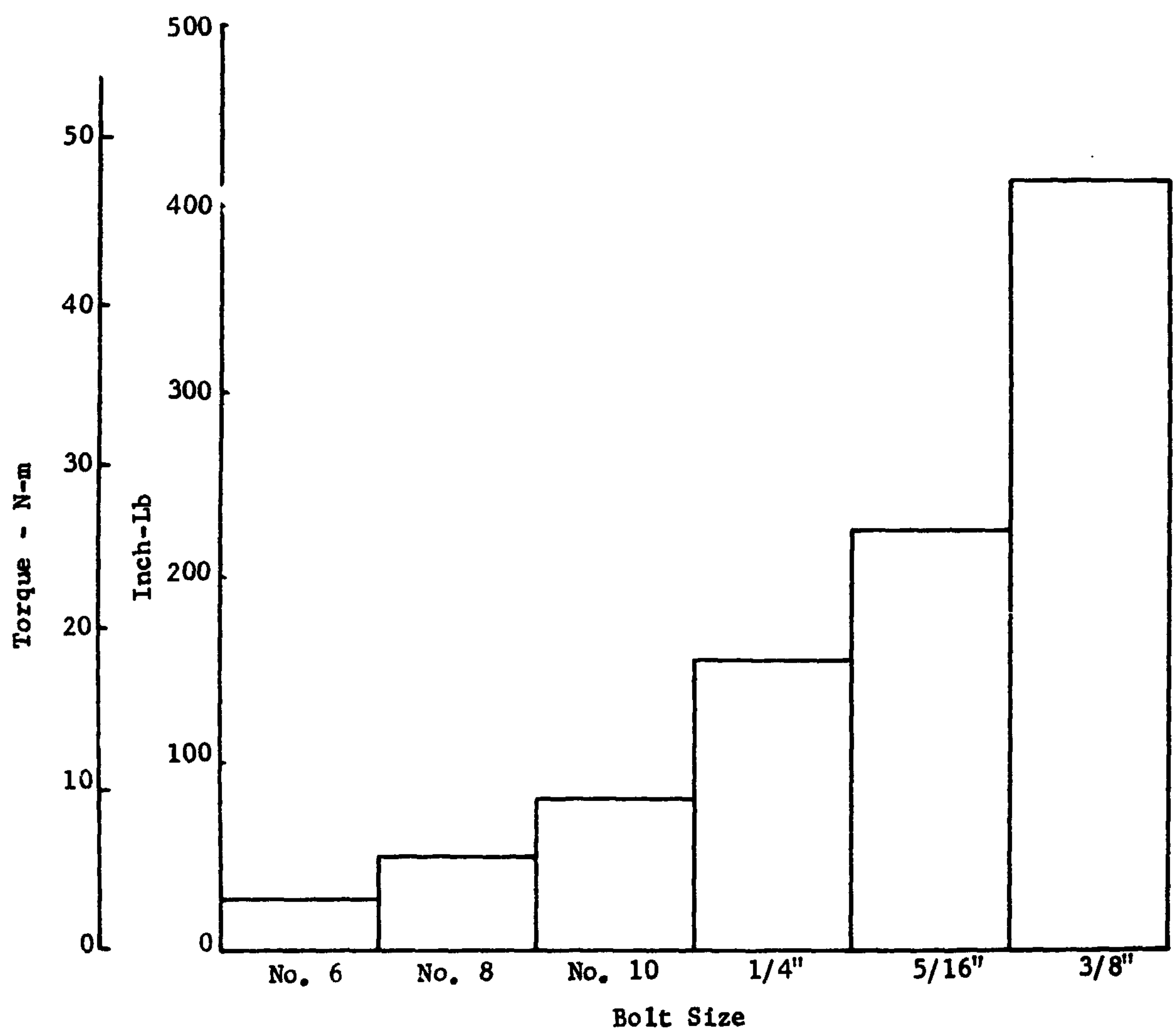


Figure IV-36 Maximum Torque Values for Removing Various Sized Bolts the four point provides more gripping surface while the 12 point provides the smallest wrench clearance and 30 degree positional symmetry. Another factor to remember is to select a shape that provides parallel gripping surfaces that oppose each other. When using a transition wrench in starting or running threads, either a socket or box end is preferred.

The internal grip or Allen wrench is considered a good design for space applications since it retains all the advantages of the socket type plus is lighter and also easier to align during capture. For either type used, a method of holding nuts and bolts must be developed. Preliminary evaluations indicate the best approach is to use captive nuts and captive bolts on all modules having a replacement potential.

Existing connectors, such as electrical and fluid types, require more skill and strength to make/break than is readily available by the proposed manipulator. Modifications would be required to incorporate the gripping force to depress the lock and provide coupling release. Another modification required is the provision for bulkhead mounting with access for operation.

Prior to defining the tool attachment configurations best suited for holding tools on an end effector, their physical characteristics must be defined. These characteristics include tool weights, actuation forces, operating throw width for handles, applicability to operation with one hand, and aligning capabilities of handles to end effector and tool to work item. Reference 10 has evaluated some of these characteristics and prepared a summary as shown in Table IV-8.

Note that the motion geometrics for the two handle pivot tools represents maximum throw rather than maximum working ranges. Some tools, such as regular pliers and channel lock pliers, require maximum throw to vary the tool working regime and therefore affect the end effector jaw width requirements to a greater extent than the tool working range throw. The common type ratchet wrench can be operated in several ways by the end effector. It can be held by the handle with the socket over the bolt head and ratcheted back and forth by operating the manipulator. This

Table IV-8 Tool Requirements/Capabilities

Tools	Size, in.			Motion (Spread), in.		Remarks
	Overall	Jaw	Handle	Handle	Jaw	
Pliers (Regular)	$6\frac{1}{2}$ to 8	$1\frac{1}{4}$	[illegible]	8	$1\frac{1}{2}$	8-oz weight, double curved milled [illegible], knurled handles
Needle Nose Pliers	6	1 3/4	$3\frac{1}{2}$	2 to 4	1 1/8	5-oz weight, slender head, knurled handles
Wire Cutters	7	2	[illegible]	5 3/4	1	12-oz weight, heavy duty, beveled nose
Wire Strippers	10	$1\frac{1}{2}$	8	$1\frac{1}{2}$	1	17-oz weight, strip 8 to 22 gage wire
Automatic Size & Vise Grips	7	$1\frac{1}{2}$	$3\frac{1}{2}$	$5\frac{1}{2}$	$1\frac{1}{4}$	14-oz weight, double curved milled jaws
Ratchet Wrench Set						
Handle	10	1 3/4	9	--	--	21-oz weight
Sockets	$1\frac{1}{2}$	$\frac{1}{2}$ to $1\frac{1}{4}$	--	--	--	19-oz weight (total)
Ball Drivers	$7\frac{1}{4}$ max	--	$6\frac{1}{2}$ max	--	--	32-oz weight, set of 12 sizes 0.050 to 5/16 in.
Open-End Wrenches or Self-Adjusting Crescent	9 max	13/16 max	$7\frac{1}{2}$ max	--	--	17-oz weight (8 wrenches)
Crimping Tool	10	1	8	3	$1\frac{1}{2}$	28-oz weight
Channel Locks	10	1	8	11 max	4	16-oz weight, seven adjustments, 2-1/8 in. usable jaw opening
Internal Snap Ring Pliers	$8\frac{1}{2}$	1	$6\frac{1}{2}$	2 5/8	1/8	7-oz weight, snap rings 1 in. diameter or greater
External Snap Ring Pliers	9	1/8	7	$1\frac{1}{2}$	$1\frac{1}{2}$	8-oz weight, snap rings 1 in. diameter or greater

can occur with the handle axis in either of two directions with respect to the end effector. A second method would be to hold the ratchet head in line with the EE X-axis and rotate as desired. An alternative, such as a long lever arm, may be required where significantly higher torques than it can generate may be required. This type information and more is needed to define tool modifications that arise from the desirability of a consistent stroke of the end effector and the need to obtain a high force/torque interface (retention system between the tool and the end effector, and to ensure that the tools can be retained by the tool container or the end effector at all times). The tools selected for interfaces with the end effector include hand tools that have operating strokes designed to be compatible with the human hand. Therefore, the end effector will be assumed to have a similar operating stroke.

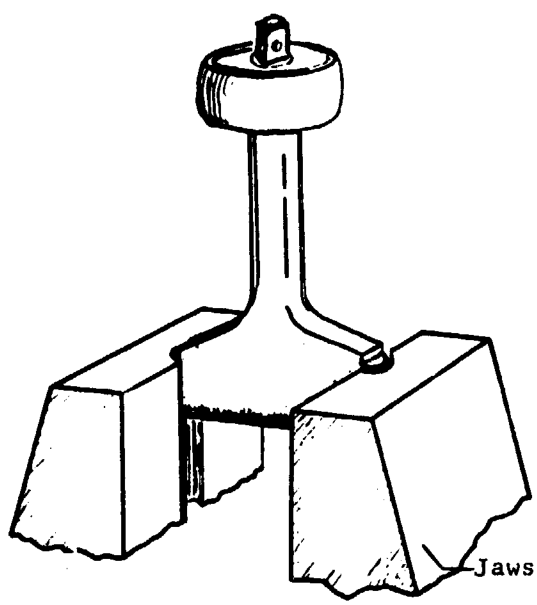
With a number of the operating motions identified and tool characteristics defined, the next step looked at feasible ways of attachment to the end effectors. For interface purposes, the tools considered may be divided into four general groups: single handled tools (Allen wrench, etc.) multi-handled tools (plier type), ones using a power take-off and ones needing electrical power. For simplicity, the design goal remains for all types of tools to be held, operated, and locked and unlocked using one arm with minimal tool-holding complexity.

If useful tools can be obtained and/or modified to be compatible in grasp and motion, then one end effector concept may be adequate. Fig. IV-37 presents different interface concepts; some resulting from on-going NASA programs while others were based on ground units.

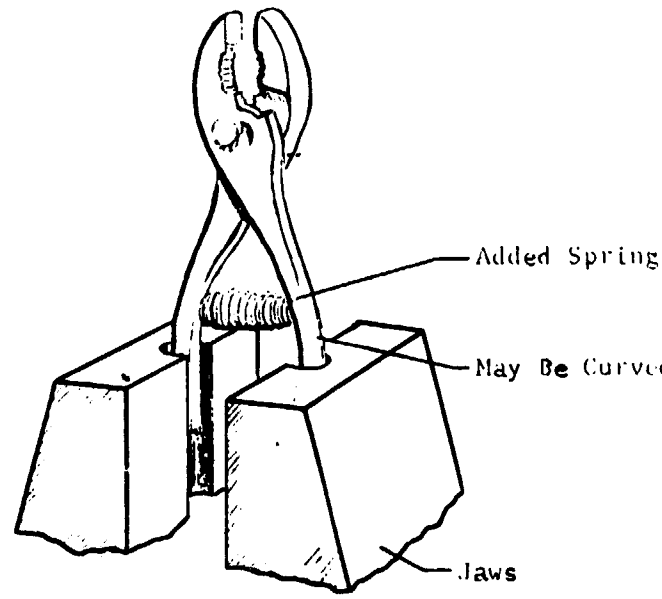
Concepts shown in Fig. IV-38 were selected because of their simplicity. Concept (a) can be used for socket applications with the big advantage being the use of the wrist roll to provide the rotational motion. Concept (b) presents the concept thinking developed in Reference 10 for a Terminator Kit Assembly (TKA). Concept (c) represents the self-contained approach where the tool being held provides all actuations required in performing its function. For this case, the wrist roll capability would be limited to approximately ± 60° and would provide a hardwire electrical quick disconnect at the mating jaw interface. Concept (d) was from Reference 11 by D. H. Dane and K. T. Blaise of NASA's MSFC in which they show some specific characteristics that a mechanical end effector needs to use hand tools for maintenance, repair, and assembly work.

The last item looked at in transition tool configuration was the tool container. Tool container concepts may be categorized in several ways - shape, accessibility, tool retention methods, adaptability/versatility to tool selection changes, etc. Again the key word was simplicity.

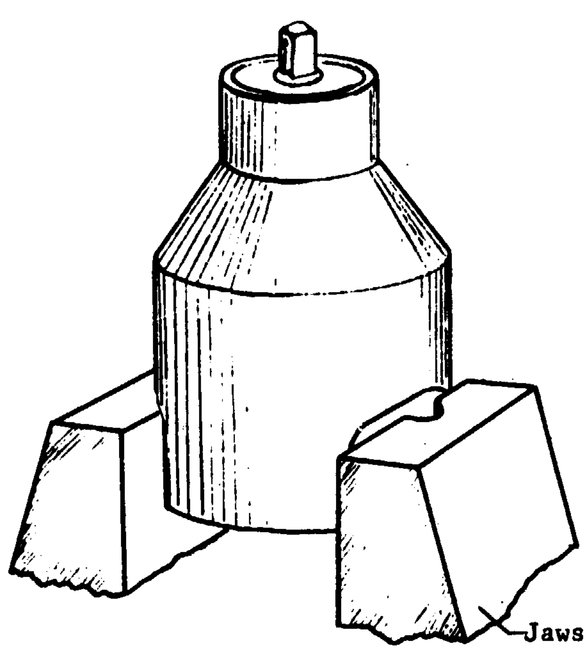
A few of the retention concepts available from other programs, most of which have already been studied and evaluated for astronaut use (not via manipulator arms), are brush-type, internal and external (Fig. IV-39).



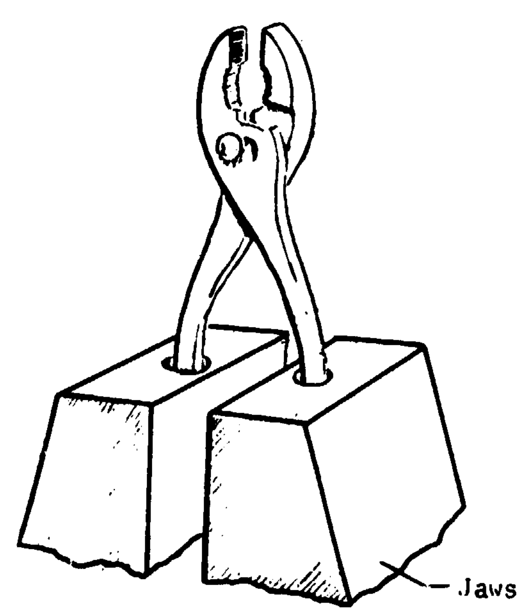
a. Single-Handle Wrench Type



b. Two-Handle Scissors Type

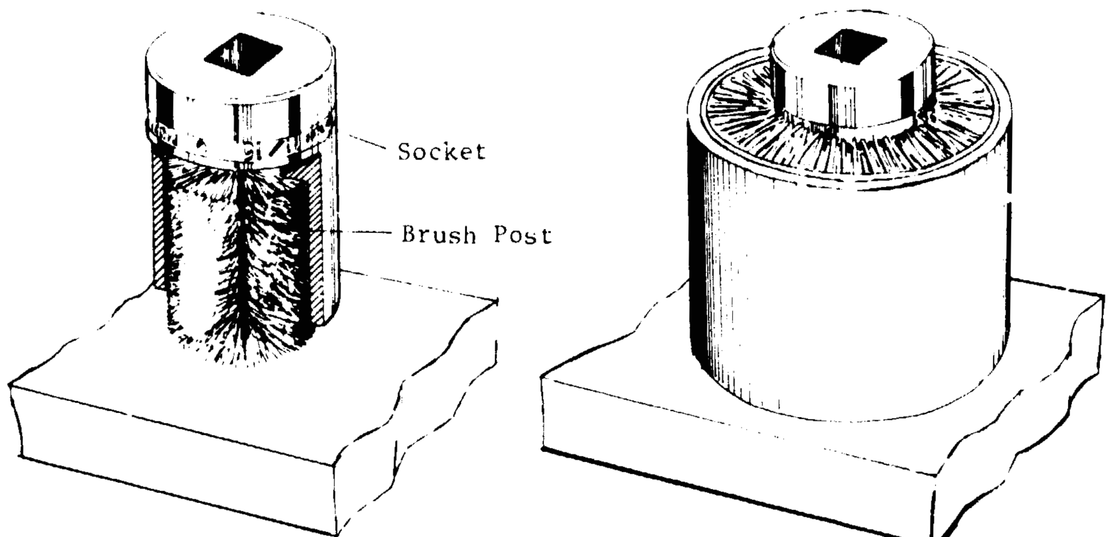


c. Self-Contained Tool Type



d. NASA Proposed Terminator Kit Assembly (TKA)

Figure IV-38 Tool/Jaw Interface Concepts



External Brush Type

Internal Brush Type

Figure IV-39 Tool Retainer Concepts

A more universal-type tool container completely compatible with most any end effector concept consists of a single rectangular tool tray that employs the plastic brush finger retention method as shown in Fig. IV-40 rather than spring clips.

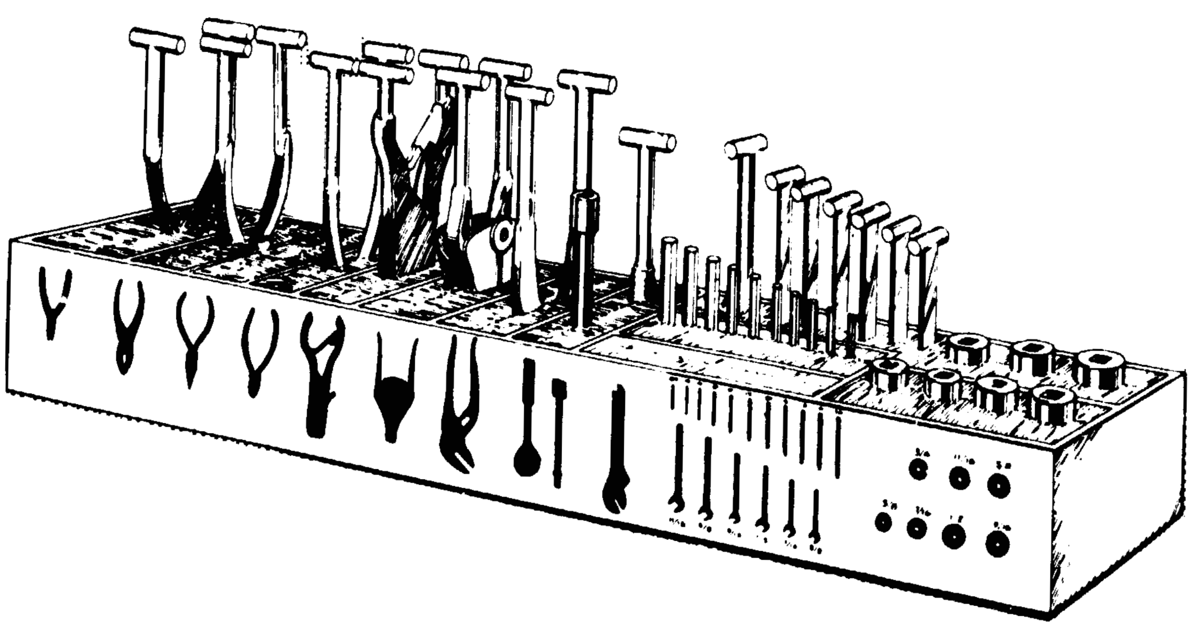


Figure IV-40 Brush Type Tool Container

4. End Effector Design Concepts

The primary emphasis during this part of the analysis was to investigate the basic functions of engage, hold and release and then apply them to a range of feasible mechanisms which could perform the functions. From this point, the evaluation considered items such as jaw configuration (dimensions and shapes), handles/or gripper, power or gear train links, and operating characteristics (jaw closing speed, sensor data feedback, etc.).

a. Grasper Types - General grasping techniques were considered in a comparison matrix as shown in Figure IV-41. These comparisons were very top level with the main purpose to reduce quickly the number of techniques for further considerations.

Preliminary evaluation results indicated three techniques have the greatest potential for space application. These techniques include scissors, vise or parallel, and insert/lock (probe). The next evaluation level considered only these three techniques in greater detail in order to assign a preferred priority. Figure IV-42 presents a comparison matrix used in determining the rating sequence. In summary, the true parallel jaw concept (I-1) was selected first based on: (1) provides a grip contact which remains constant during the grip cycle, (2) presently considered the state-of-the-art manipulator end effector, and (3) com[illegible] and tools have been developed which interface with the parallel jaw ty[illegible] end effector.

The alternate or second place selection was the insert and lock concept (I-4). This selection was chosen based on: (1) design simplicity and light weight and (2) ease of aligning this device with the capture handle.

The scissors concept (I-3) was given third place and stayed in the running based on its capability to provide a maximum throw opening.

b. Jaw Configurations - The jaw configuration concepts were derived on their capability to function when attached to a scissor, vise or insert/lock grasping device. These grasping techniques can be expanded and

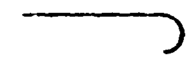
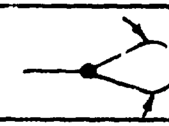
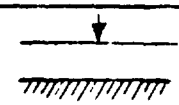
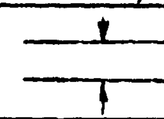
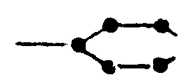
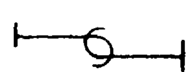
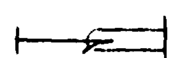
TECHNIQUES	GEOMETERIES	MODIFICATIONS	ADVANTAGES	DISADVANTAGES
Hook			Simple Design	Req. Exposed Handle
Scissors			Simple Design Large Grip Width	Items Forced Away From Scissor Action
Vise or Parallel			Applies Equal Force	Round or Wet Items Twist & Difficult Alignment
Wrapping Around (Multi Joints)			Takes Shape of Object	Complex Design
(Multi Fingers)			Less Force Req. to Hold Item	
Insert & Lock	 (Male/Female)	Not Pract. (Female/Male)	Simple Design Ease of Alignment	Lock Failure
Interlocking Fibers			Ease of Alignment	Not a Positive Hold
Magnetic	N/A	--	Ease of Alignment	Not a Positive Hold, Req. Special Material, EMI Problems

Fig. IV-41 Grasping Techniques for End Effectors

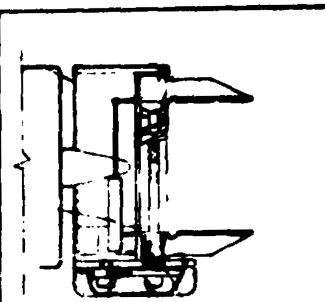
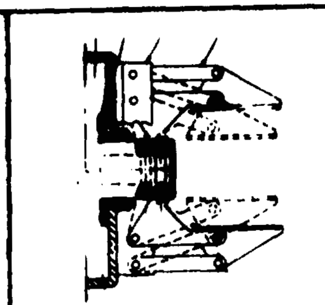
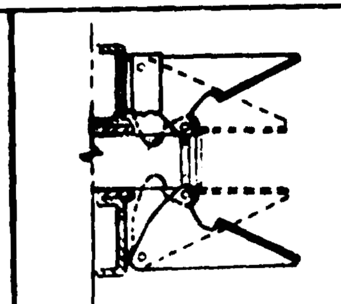
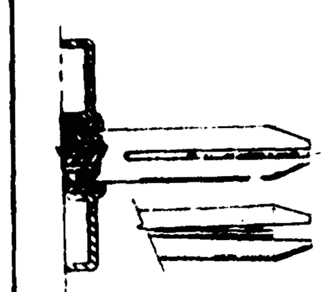
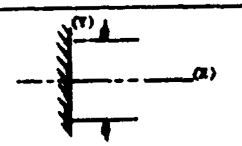
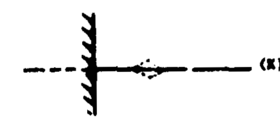
Grip Technique (Artist Concept) / Motion Linkage Parameters	 I-1	 I-2	 I-3	 I-4
1. Basic Jaw Grip Motions				
2. Motion Description	Parallel Vise. Where the grip contact point remains stationary.	Parallel motion to the X-axis with a translational arc of ± displacement.	Scissor Motion developed from either a common pivot point or separated pivot points.	Probe insert and lock.
3. Motion directions which provide desired jaw action	a) Slide along the (Y) axis. b) Rotation with screw parallel to (Y) axis	Dual pivots and links on each jaw.	a) Common pivot through center. b) Primary pivot points separated and fixed.	Locking feature can be provided by a cam action or inclined plane.
4. Force input shaft, motion requirements for Item 3	a) Rotation - cable drive b) Rotation - Differential	Linear drive shaft or Rotating Screw drive	a) & b) Linear drive shaft or rotating screw drive	Linear drive shaft or rotating screw drive
5. Remarks	Presents least number of pivot points in the motion linkage, little slop in system.	Requires more moving pivot points than other concepts considered.	Provides simple linkage design, one pivot point for each jaw, must be slotted.	Provides simple linkage design to activate locking device.

Figure IV-42 Projected Linkage Motions Comparison made more flexible by incorporating interchangeable jaw pads into the end effector design. Figure IV-43 presents three different concepts considered feasible in defining the interface attachment between jaw contact tongs and the power link. In general, the power link provides motion of either continuous rotation or linear travel along the end effector X axis. During this study, the interface between the power link and jaw configuration was considered common in that none of the concepts considered had a big impact on driving the jaw configuration.

Jaw configurations conceived for general manipulator application are presented in Figures IV-44, IV-45 and IV-46 along with preliminary comparisons of system characteristics. Jaw concepts presented have been separated into three groups: vise (I), scissor (II), and insert/lock (III).

During the jaw comparison analysis, some basic assumptions were used to simplify comparisons. Concepts I-1 through I-6 employ an equal parallel or vise motion to grasp and hold objects. Distance between the jaws gripping surface was baselined at 4 inches maximum. A realistic handle size for gripping purposes was found to range from 3/8 to 1 inch thickness. Therefore, a 1 inch handle was assumed for defining allowable angular and displacement misalignments.

Concepts II-1 through II-6 use a scissors motion to grasp objects. Distance between the jaws for maximum opening was baselined at 6.3 inches. This was possible due to the capability inherent with the scissors to open to approximately 130 degrees. The big disadvantage with the scissors concept is in the increasing and unequal point force application. This generates a force vector that physically pushes the handle away from the gripping jaws.

Concepts III-1 through III-3 apply the insert and lock technique which is similar to some of the docking devices. The first concept looked at (III-1), had a single probe and an inherent locking device. This concept

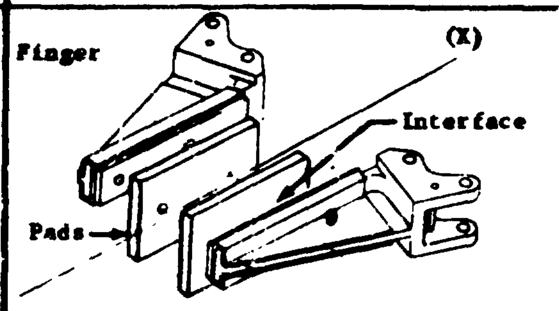
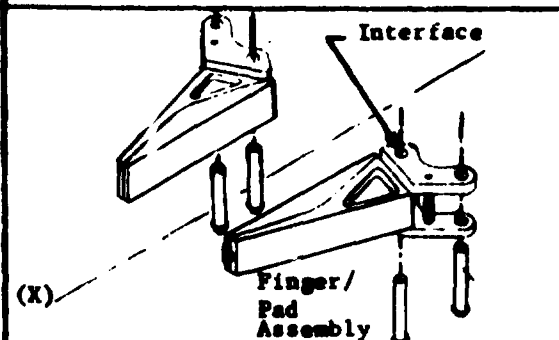
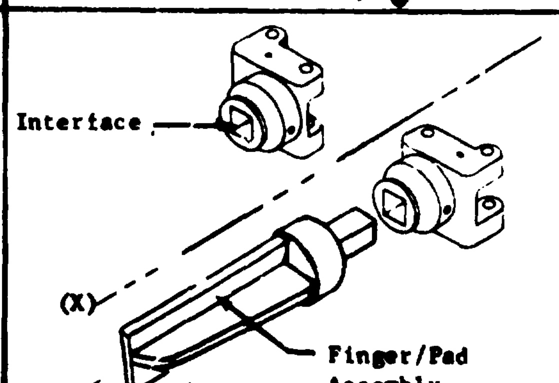
Jaw Interchangeability Concepts	Concept Schematic	Description	Remarks
Replaceable Jaw Pads		The pad is attached to a common finger, provides the capability to design any specific shape for grasping and holding.	Simple design, medium time required to interchange pads. Modification to the concept schematic would be clip-on pads.
Replace Pad/Finger Assembly at Pivot Points		The pad and finger are combined assembly or manufactured from one piece, provides greater flexibility in grasper design configuration.	Basic design, moderate time required to interchange pad/finger assembly.
Reference pad/finger assembly at socket type joint.		The pad and finger assembly are held in a slip fit socket. Friction, detent or set screw may be used to hold this assembly.	Simple design, fast interchange of pad/finger assembly. Compatible with interchangeability of general purpose tools (pliers, torque wrench, etc.).

Figure IV-43 Evaluation of End Effector Jaw Interchangeability Concepts

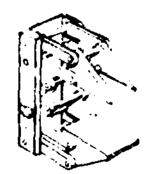
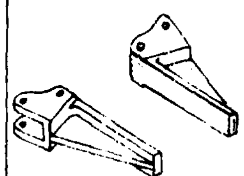
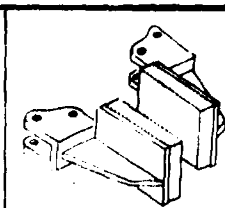
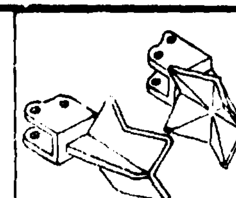
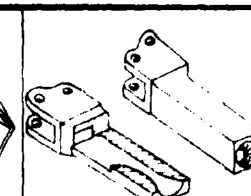
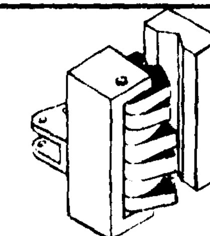
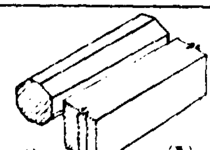
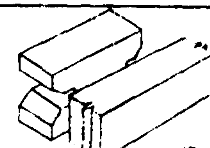
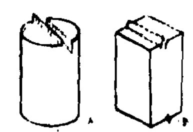
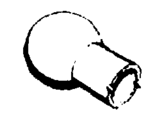
Characteristics \ Concept	 I-1 Parallel Vise	 I-2 Standard Flat Face	 I-3 Resilient Material	 I-4 Trailer Hitch	 I-5 TKA Jaw Concept	 I-6 Segmented Vise
1. Compatible Capture Hardware					Hold Service Tools: . Any tool with parallel flat surfaces. . Any tool requiring a common pivot point scissors action (Pliers, wire cutters, etc)	Good For Odd Shapes: Round bar to Triangular rod
2. Applicable Baseline Requirements (Task 2) . Description . Closing Velocity . Max. Grip Width . Grasp Depth Range	Basic Parallel Concept Curvilinear Motion (2 in/sec) 10 cm (4 in) 4 - 10 cm (1.5 - 4 in)	Standard Vise Jaws (2 in/sec) 10 cm (4 in) 4 - 10 cm (1.5 - 4 in)	Resilient Material Takes Shape of Item Held (2 in/sec) 10 cm (4 in) 4 - 10 cm (1.5 - 4 in)	Similar to Ball and Socket Concept (2 in/sec) 10 cm (4 in) 4 - 10 cm (1.5 - 4 in)	Concept Proposed by Dane and Claise of NASA-MSFC to hold hand tools for maintenance work. (2 in/sec) 10 cm (4 in) 4 - 10 cm (1.5 - 4 in)	Segments snugly pinned to one jaw with hardened dowel pin. (2 in/sec) 10 cm (4 in) 4 - 10 cm (1.5 - 4 in)
3. Allowable Angular Misalignment P, Y, and R	(B) ± 0.524 rad (± 30 deg)P ± 0.524 rad (± 30 deg)Y ± 0.088 rad (± 5 deg)R Ref	(B) ± 0.524 rad (± 30 deg)P ± 0.524 rad (± 30 deg)Y ± 0.088 rad (± 5 deg) R	(B) ± 1.34 rad (± 80 deg)P ± 0.524 rad (± 30 deg) Y ± 3.14 rad (± 180 deg)R	± 1.34 rad (± 80 deg)P ± 0.524 rad (± 30 deg)Y ± 3.14 rad (± 180 deg)R	(TBD) deg)P deg)Y deg)R	± 0.088 rad (± 5 deg)P ± 0.088 rad (± 5 deg)Y ± 0.088 rad (± 5 deg)R
4. Allowable Displacement Misalignment X, Y, Z (Estimated, Assuming a Functional Handle Size of 1")	± 3.8 cm (± 1.5 in)X ± 3.8 cm (± 1.5 in)Y ± 2.54 cm (± 1 in)Z	± 3.8 cm (± 1.5 in)X ± 3.8 cm (± 1.5 in)Y ± 0.63 cm (± 0.25 in)Z	± 3.8 cm (± 1.5 in)X ± 3.8 cm (± 1.5 in)Y ± 2.54 cm (± 1.0 in)Z	± 1.27 cm (± 0.5 in)X ± 3.8 cm (± 1.5 in)Y ± 1.27 cm (± 0.5 in)Z	(TBD) in)X in)Y in)Z	± 0.63 cm (± 0.25 in)X ± 3.8 cm (± 1.5 in)Y ± 0.63 cm (± 0.25 in)Z
5. Capturability, X, Y, Z	Requires moderate alignment accuracy, self-aligning in Y-axis. (Req. joint relaxation)	Requires moderate alignment accy. self-aligning in Y-axis	Requires moderate alignment accuracy	High angular misalignment capability	Requires accurate alignment	Requires accurate initial alignment
6. Viewing of Alignment	Small misalignment may be difficult to detect	Small misalignment may be difficult to detect, however, jaw grip is easier to view	Small misalignment may be difficult to detect	Difficult to detect alignment along X-axis	Difficult to align special end tools	Difficult to view alignment
7. Capture Hardware Compatibility	Best handle configuration has flat parallel surfaces 180 deg apart	Requires flat parallel surfaces 180 deg apart, jaw surface prepared to allow no slip at 20 lb	Will accept odd shapes requiring low grip forces	Will accept ball, T handle and shaped rods	Will accept same handle types as concept I-1 and special tools in jaw ends	Difficult to view alignment
8. Design and Build Complexity	Low complexity	Low complexity	Medium complexity	Low complexity	High complexity	Medium complexity
9. Remarks	Most common jaws for universal tasks. Applies forces along parallel jaw grip surface	See concept I-1	Jaws used for various tasks that require low grip forces. Resilient material on jaw provides capability to grip irregular shapes.	The ball allows large angular misalignment in capture procedures. & metal shaped handles may also be applicable to this concept.	Under study as a possible prosthetic device for amputees. Has possible space application, requires work on simplifying alignment of tool to jaw interface.	Each segment can only move in a small arc in a plane perpendicular to the dowel axis. Segments auto. change their position to match the shape of irregular objects.

Figure IV-44 Parallel/Vise Concepts Comparisons

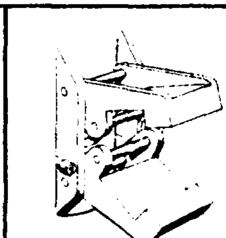
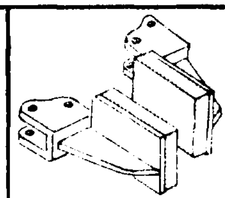
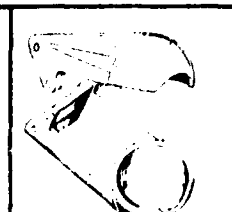
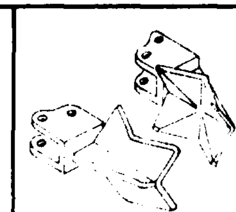
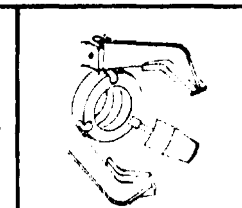
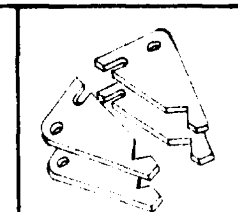
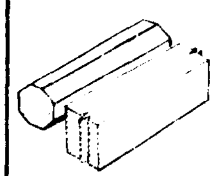
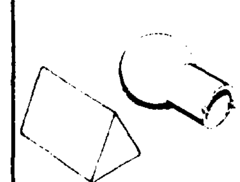
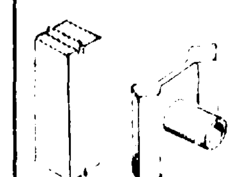
Concepts / Characteristics	 II-1 Scissors	 II-2 Resilient Jaw Mat'l	 II-3 Ball & Socket	 II-4 Trailer Hitch	 II-5 Three To[illegible]	 II-6 Notched Jaws
1. Compatible Jaw to Handle						
2. Applicable Baseline Requirements (Task 2) . Description . Closing Velocity . Max. Grip Width . Grasp Depth Range	Basic Scissors Concept, Jaw Tips Keep Material in Jaws. (2 in/sec) 16 cm (6.3 in.) 4-10 cm (1.5-4 in.)	Resilient Material Used on Jaw Pads, Takes Shape of Item Held (2 in/sec) 1.6 cm (6.3 in.) 4-10 cm (1.5-4 in.)	Ball & Socket Concept, Requires Close Alignment (2 in/sec) 1.6 cm (6.3 in.) 4-10 cm (1.5-4 in.)	Similar to Ball and Socket Concept (2 in/sec) 16 cm(6.3 in) 4 - 10 cm (1.5 - 4 in)	(2 in/sec) 16 cm (6.3 in) 4 - 10 cm (1.5 - 4 in)	Special V Shaped Jaw, Used on MDM, 14 Ft Arm. (2 in/sec) 6.35 cm(2.5 in) 2.54 cm (1 in)
3. Allowable Angular Misalignment P, Y, and R	±0.175 rad (±10 deg)P ±0.175 rad (±10 deg)Y ±0.088 rad (±5 deg) R	±0.175 rad (± 10 deg)P ±0.524 rad (± 30 deg)Y ±0.088 rad (± 5 deg) R	±1.39 rad (± 80 deg)P ±0.52 rad (± 30 deg)Y ±3.14 rad (±180 deg)R	± 1.39 rad (± 80 deg)P ± 0.52 rad (± 30 deg)Y ± 3.14 rad (± 180 deg)R	± 0.52 rad (± 30 deg)P ± 0.52 rad (± 30 deg)Y ± 3.14 rad (± 180 deg)R	± 0.35 rad (± 20 deg)P ± 0.088 (± 5 deg)Y ± 0.52 rad (± 30 deg)
4. Allowable Displacement Misalignment X, Y, Z (Estimated, Function of Handle Size (Assume 1/2 to 1")	±2.54 cm (±1.0 in)X ±6.35 cm (±2.5 in)Y ±2.54 cm (±1.0 in)Z	±5.0 cm (±2 in) X ±7.6 cm (±3 in) Y ±2.54 cm (±1.0 in)Z	±0.16 cm (±0.063 in)X ±6.35 cm (±2.5 in)Y ±1.27 cm (±0.5 in)Z	± 1.27 cm (± 0.5 in)X ± 6.35 cm (± 2.5 in)Y ± 1.27 cm (± 0.5 in)Z	± 2.54 cm (± 1.0 in)X ± 6.35 cm (± 2.5 in)Y ± 6.35 cm (± 2.5 in)Z	± 0.63 cm(±0.25 in)X ± 1.27 cm (± 0.5 in)Y ± 2.54 cm (± 1.0 in)Z
5. Capturability, X, Y, Z	Requires Moderate Alignment Accuracy	Requires Moderate Alignment Accuracy	Requires Accurate Alignment in X + Y Plane	High angular misalignment capability	Angular misalignment capability	Requires accurate initial alignment (has some self-aligning)
6. Viewing of Alignment	Small Misalignment May be Difficult to Detect	Small Misalignment May be Difficult to Detect	Difficult to Detect Alignment Along X Axis	Difficult to detect alignment along X-axis	Good alignment if TV lens centered	Excellent cue of alignment if TV lens capable of viewing side & top
7. Capture Hardware Flexibility	Capture Handle in Z Axis, Square Shape to any Shapes with Flat Parallel Surfaces ( )	Will Accept Odd Shapes Requiring Low Gripping Forces. Capture handle in Z and X axes.	Limited to Ball and Socket Hardware.	Will accept a ball to a T Handle or a shaped rod	Limited to a ball or triangular rod	Limited to square handle. Item B shows gripping concept for transition tools
8. Design and Build Complexity	Low Complexity	Medium Complexity	Medium Complexity	Low complexity	High complexity	Low complexity
9. Remarks	Jaws Used for Various Tasks, Have Max. Opening, Alignment Critical, Primary Use, Payload Servicing.	Jaws Used for Various Tasks that Require Low Grip Forces. Resilient material on Jaws Gives Wide Range of Shapes that can be Gripped.	The Ball and Socket Capture Technique Allows Great Angular Freedom in Handle Capture Procedures.	Greater flexibility to ease of alignment then concept II-3.	Modification of the ball socket technique, provides reduced alignment requirements	This concept being fabricated for MMC 14 ft arm. For service function distance between jaws to be greater and include solid angle between jaw frame.

Figure IV-45 Scissors Concepts Comparisons

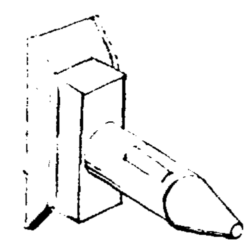
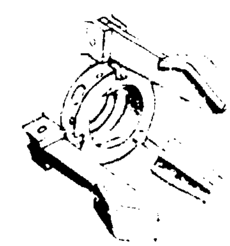
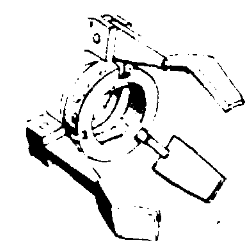
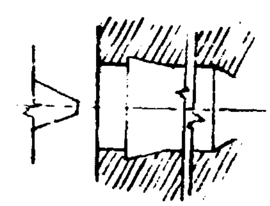
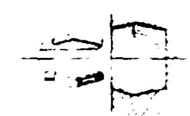
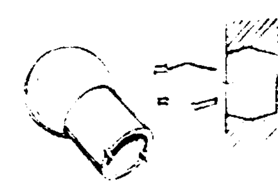
Concepts / Characteristics	 III-1 Insert/Lock	 III-2 Insert/Expand	 III-3 Dual Action Grasp
1. Compatible Jaw to Handles			
2. Applicable Baseline Requirements (Task 2) . Description . Closing Velocity . Max. Grip Width . Grasp Depth Range	4-10 cm (1.5 - 4 in) 1.27 - 2.54 cm (½ - 1 in)	4 - 10 cm (1.5 - 4 in) 1.27 - 2.54 cm (0.5 - 1 in)	Internal and External Grasp 4 - 10 cm (1.5 - 4 in) 1.27 - 2.54 cm (0.5 - 1 in)
3. Allowable Angular Misalignment P, Y, and R	± .05 rad (± 3 deg)P ± .05 rad (± 3 deg)Y ± 3.14 rad (± 180 deg)R	± .017 rad (± 1 deg)P ± .017 rad (± 1 deg)Y ± 3.14 rad (± 180 deg)R	± .017 rad (± 1 deg)P ± .017 rad (± 1 deg)Y ± 3.14 rad (± 180 deg)R
4. Allowable Displacement Misalignment X, Y, Z (Estimated, Assuming a Functional Handle Size of 1")	N/A in X ±0.63 cm(± 0.25 in)Y ±0.63 cm(± 0.25 in)Z	± 1.25 cm (± 0.5 in)X ± 0.63 cm (± 0.25 in)Y ± 0.63 cm (± 0.25 in)Z	± 1.27 cm (± 0.5 in)X ± 0.63 cm (± 0.25 in)Y ± 0.63 cm (± 0.25 in)Z
5. Capturability,X,Y,Z	Requires accurate alignments	Requires accurate alignment	Angular misalignment capability
6. Viewing of Alignment	Alignment cues would be useful	Good viewing cue if TV centered	Good viewing cue if TV lens centered
7. Capture Hardware Flexibility	Limited to a compatible insert and expand type receptacle	Limited to an insert and expand type receptacle	Good flexibility for capture of different shaped hardware
8. Design and Build Complexity	High complexity	High complexity	High complexity
Remarks	Provides clean worksite surface and self aligning capability	Jaws will expand once in receptacle, holding while final alignment is made	This concept provides dual use, as both an external grasp or align with internal receptacle and expand

Figure IV-46 Insert and Lock Concepts Comparisons has many possible options and should be considered for special purpose applications.

Results from this generalized end effector study have been collectively evaluated. Items having merit for further design considerations in Task 4 have been summarized in Table IV-9.

Table IV-9 End Effector Requirements Summary

Items and Functions	Design Criteria Recommendations
Interfaces, Functional	
Wrist:	
Degrees-of-freedom	Three (Pitch, Yaw, Roll)
Roll	Continuous Rotation
Speed	0.2 rad/sec (11.5 deg/sec) at full load
Torque	20 N-m (15 ft-lb) nom.
Wrist/End Effector	Interchangeable, manual
Worksite: (Guidelines)	
Task Functions	Remove/Replace Modules Break/Make Connections
Manipulator/Worksite	Assume one rigid body
Module Locations	Near Surface for Direct Access
Module Removal	Linear Motion; 1 meter min.
Illumination	TBD
Interface: Physical	
Wrist:	
Wrist/End Effector Connector	10 cm (4 inch) O.D. max.
Electrical	Hardwire
Worksite:	
Module Size Accom. (max)	1 x 1 x 1 m (3.3 x 3.3 x 3.3 ft)
Module Size Accom. (min)	0.15 x 0.15 x 0.15m (0.5 x 0.5 x 0.5 ft)
Module Mass	150 kg (330 lb)
Handles	

Table IV-9 End Effector Requirements Summary (Cont'd)

Items and Functions	Design Criteria Recommendations
<u>End Effector</u>	
Jaw Configuration	Parallel/Vise, Altern.: Insert/Lock
Grip Throw (Max)	7.6 cm (3 in) min
Grip Force (Max)	44.5 to 89 N (10 to 20 lb)
Grip Torque (Applied)	20.2 N-M (15 ft-lb)
Grip Speed	5 cm/sec (2 in/sec)
Jaw Actuation Linkage	Cams, Screw Thread, Pivot Links (Sys. Design Dependent)
Power Source	28 Volt, DC, Electric Motors
Actuators	Gear Trains and Shafts Compatible with continuous Roll Joint
Jaw Dimensions	
Grip Width	1.74 - 3.5 cm (0.75 to 1.5 in)
Grip Length	2.5 - 5.1 cm (1.0 to 2.0 in)
Total Gripping Depth	5.1 - 7.6 cm (2.0 to 3.0 in)
Design Features	Interchangeable Jaws
<u>Sensors</u>	
Position and Alignment	Visual: Indirect, Depth Sensor Coil
Force Feedback (Roll Torque)	Design Dependent
Rate (Roll)	Tachometers
Position (Roll and Jaw Throw)	Potentiometers
Grip Force	Current, Motor
Contact	Visual only.

E. SYSTEM CONCEPT SELECTION

A review of the manipulator system concepts was conducted by the NASA at which time two concepts were selected for further consideration: the first for preliminary design and the second as an alternate.

1. Configuration

The manipulator configuration selected was the general purpose six degree of freedom articulated arm for application to satellite maintenance and servicing activity. This concept, previously shown in Fig. IV-11, was baselined to incorporate the baseline requirements shown in Table IV-10.

A second concept, previously shown in Fig. IV-4(b) and requiring only four degrees of articulation, was selected as an alternate candidate to be further investigated by the NASA.

Table IV-10 General Purpose Manipulator Baseline Requirements

Parameter	Requirement
Gimbal Sequence	Translation: Yaw, Pitch, Pitch Rotation: Pitch, Yaw, Roll
Length	Shoulder to End Effector: 2.74 m (9 ft)
Working Volume	Hemispherical over FFTS Docking Interface
Tip Force	At Maximum Extension: 44.5 N (10 lb)
Tip Torque	20.2 N-m (15 ft-lbs)
Velocity	At Maximum Extension: $\leq$ 0.6 m/sec (2 ft/sec)
Mass	$\leq$ 45.4 Kg (100 lbs)

Each of these concepts provide the ability to remove and replace modules as required during the servicing of satellites with the 6 degree-of-freedom concept providing more flexibility to the servicing functions. Additionally, it was recognized that the technology developed in the preliminary design of the 6 degree-of-freedom concept would be directly applicable to the alternate concept.

2. Controllers

The controller types selected for further study included two 3-DOF rate controllers for unilateral rate control and the 6-DOF vertical slider controller concept for both unilateral and bilateral position control as shown in Figs. IV-17 and 22. Force sensing for the bilateral technique was to be based upon positional errors which eliminated the need for either distributed strain gauges on the arm or a strain gauge array at the end effector.

3. Control Technique

The control technique selected for investigation during the preliminary design phase for application to the manipulator configuration consisted of the range/azimuth/elevation/rotation technique, (Section IV-C.3) with the following options to be investigated during the man-in-the-loop simulations: unilateral rate, unilateral position, and bilateral position. The primary criteria for selection of this technique was the inherent simplicity of implementation, as the control technique is matched to the manipulator configuration characteristics.

4. End Effector

The end effector concept selected for the manipulator system preliminary design was a parallel jaw type based upon general purpose applications. The end effector requirements were to be based upon the recommendations of Section IV-D as previously summarized in Table IV-9.

V. DETAILED REQUIREMENTS ANALYSIS AND TRADE STUDIES

Based upon the manipulator system concept selected for the preliminary design phase, a detailed analysis of the configuration was conducted to establish those requirements that are key elements in the preliminary design of the manipulator system. The results of these analyses, as well as man-in-the-loop simulations, were used to form the framework for the overall design.

A. CONFIGURATION ANALYSIS

1. Joint Angular Travel

The joint angular travel limits are derived from the reach requirements, the working volume, and the typical motions required to effect the task activity.

a. Shoulder Yaw - The angular travel limits on the shoulder yaw gimbal are $\pm$ 200 degrees. This was established, as illustrated in Fig. V-1, to enable continuous activity on either end of the FFTS whether for satellite servicing from an alternate docking location or for stowage of the modules on the side or rear of the FFTS.

b. Shoulder Pitch - The angular travel limits on the shoulder pitch gimbal are 0 to 180 degrees. This enables the manipulator to be positioned anywhere on the hemispherical surface as shown in Fig. V-1.

c. Elbow Pitch - The angular travel limits on the elbow pitch gimbal are 0 to 180 degrees. This provides the ability to position the end effector of the manipulator, in conjunction with the shoulder pitch and yaw gimbals, any place within the hemispherical volume as illustrated in Fig. V-1.

d. Wrist Pitch - The angular limits on the wrist pitch gimbal are baselined at $\pm$ 90 degrees. However, it should be noted that additional

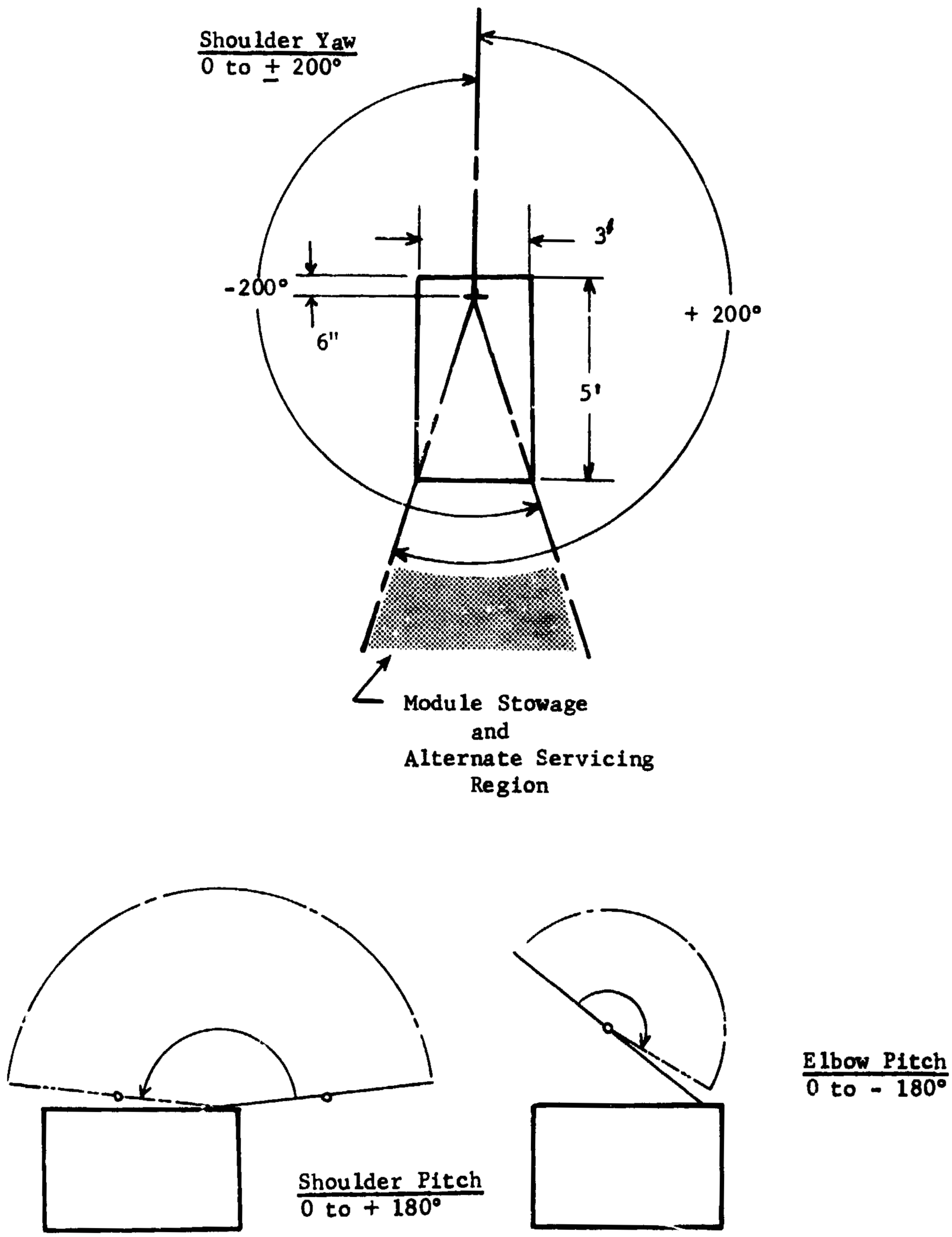


Figure V-1 Joint Angular Travel Limits

angular travel, up to $\pm$ 125, was considered for the wrist pitch. As illustrated in Fig. V-2, with the largest serviceable module (1 x 1 x 1m) and assuming a 36 cm (14 in) wrist, contact with the main arm does not occur until the wrist pitch gimbal is rotated approximately $\pm$ 125 degrees. Another area, in which a large angular travel requirement arises, is in the removal of a module while attempting to use the maximum manipulator reach available. As seen in Fig. V-2, while the wrist pitch angle limit exceeds $\pm$ 90°, this is easily avoided if the alternate technique illustrated in Fig. V-2 is used. This technique also maximizes the main manipulator arm-module clearance during the module removal. Therefore, to simplify the mechanical design, the limits on the wrist pitch gimbal will be $\pm$ 90°.

e. <u>Wrist Yaw</u> - The wrist yaw limits are established in a similar manner to that of wrist pitch, with one exception. When the wrist yaw angle is $\pm$ 90 degrees, a singularity occurs in that one motion direction of

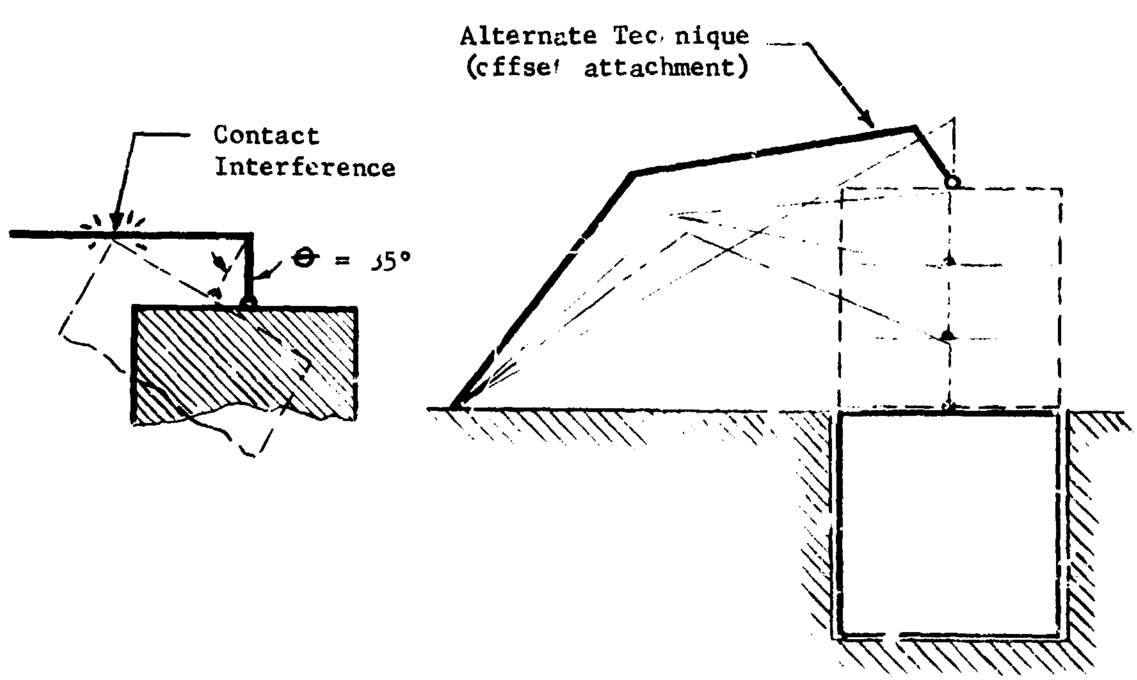


Figure V-2 Wrist Angular Travel

the wrist is lost. To avoid loss of this motion*, the second degree-of-freedom should remain less that ± 90 degrees. Therefore, while the mechanical design will still be identical to that of the wrist pitch, a ± 85 degree operational limit is baselined.

f. <u>Wrist Roll</u> - The wrist roll, primarily to provide operational and functional flexibility within the general purpose manipulator, is continuous.

g. <u>Summary</u> - The baseline manipulator will have joint angular travels as specified in Table V-1.

Table V-1 Manipulator Joint-Angular Travel

	Yaw (deg)	Pitch (deg)	Roll (deg)
Shoulder	+ 200 to - 200	0 to + 180	-
Elbow	-	0 to - 180	-
Wrist	+ 85 to - 85	+ 90 to - 90	Continuous

2. <u>Joint Accuracy</u>

An approximation of the positional error, ΔR, resulting from angular errors in the manipulator joints is given by

$$\Delta R = \left[(L\Delta\psi_S)^2 + (L\Delta\theta_S + L/2\Delta\theta_E)^2\right]^{1/2}$$

as illustrated in Fig. V-3. Assuming an equal angular error, $\Delta\theta$, in each joint then

$$\Delta R = \left[(L\Delta\theta)^2 + (L\Delta\theta + L/2\Delta\theta)^2\right]^{1/2}$$

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* Primarily a requirement based upon the use of control techniques other than joint-by-joint switch and range/azimuth/elevation.

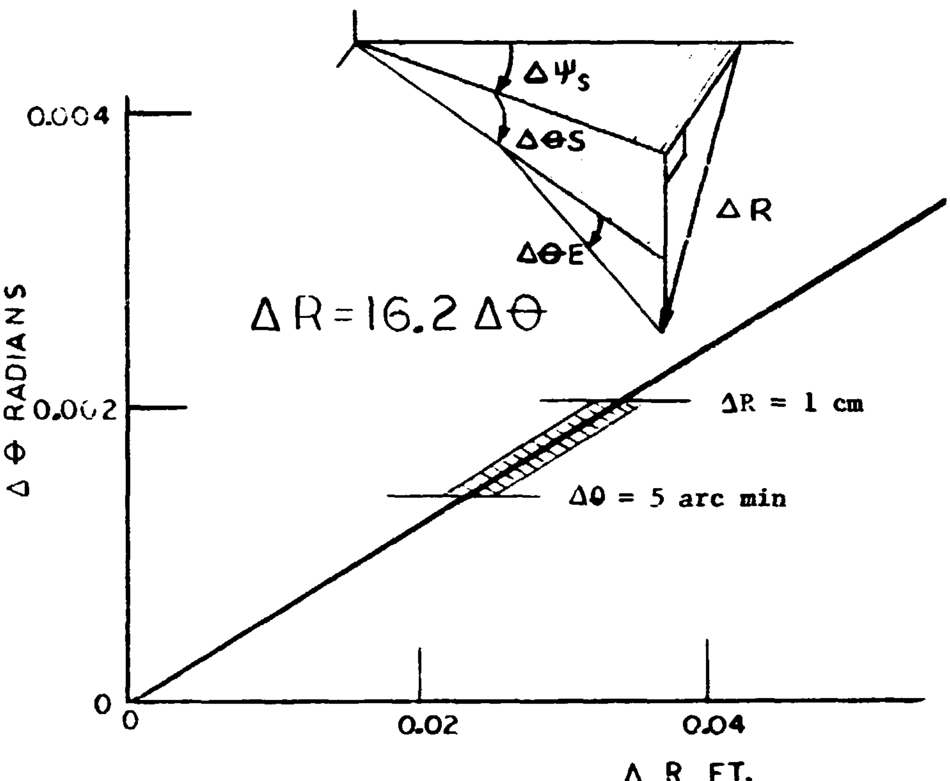


Figure V-3 Joint Positional Accuracy

or

$$\Delta R = \sqrt{13}/2\ L\Delta\theta.$$

With L = 9 ft,

$$\Delta R = 16.2\ \Delta\theta$$

This expression is plotted in Fig. V-3.

A reasonable positional error for the manipulator is about 1 cm. Additionally, from past experience, 5 arc-minutes per joint is a good approximation of backlash which would develop a maximum of 0.75 cm error. Therefore, the joint accuracy requirement will be established as no greater than 6 arc-minutes (0.1°) per joint.

3. Elbow Joint Considerations

To provide maximum manipulator volumetric coverage, the elbow joint angular travel requirement was established as 0 to 180 degrees. In addition, since the present FFTS program guidelines require the manipulator to be stowed on the ground and while in the Shuttle cargo bay during launch, orbit, deorbit and earth return, it is advantageous to assure the stowed length of the manipulator will not exceed the maximum length of the baselined FFTS or 1.52 m (5 ft).

A number of elbow joint concepts which enable the manipulator to be "folded in half" were identified as shown in Fig. V-4. The concepts start with a simple type and advance to the more complex configurations. Concept 1 was eliminated due to its inability to satisfy the stowage requirements. Concept 5 was eliminated based on its increased complexity and higher number of moving parts. This left concepts 2, 3 and 4 with no clean cut or obvious rationale for further elimination.

Based upon technical judgment, Concept 2 was selected as it provided the best joint concept for transferring the wiring across the elbow and out to the wrist.

4. Stowage Considerations

With the elbow joint having the ability to fold in half, several stowage configurations were investigated as shown in Fig. V-5.

Concept (a) enables the use of equal length arm segments. However, a support cradle for the wrist, above the FFTS mold line, would be required. The remaining concepts all have unequal segment lengths with (c) and (d) providing nearly equal segments.

Concept (d) was selected in that the stowed configuration is more nearly aligned along the FFTS mold line.

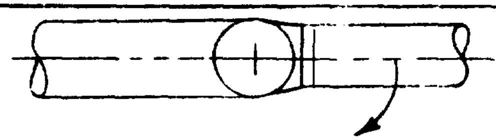
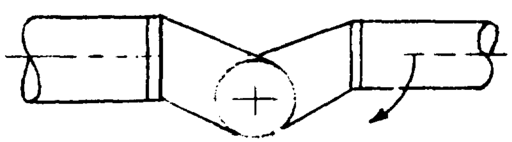
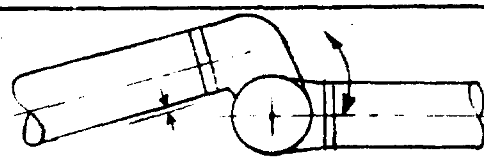
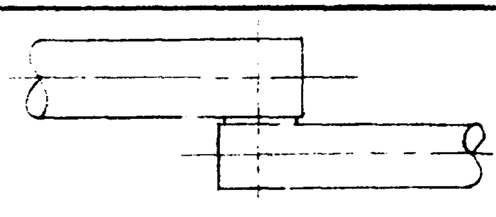
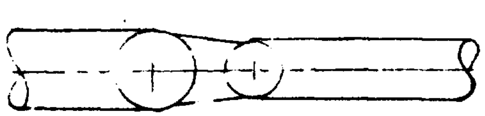
No.	Concept Schematic	Description	Advantages	Disadvantages
1		Inline Joint with a Yoke Structure	Segment symmetry	Angular travel limited to less than 180 deg. Requires larger yoke. Does not permit parallel stowage.
2		Dual Transition Sections which locates the joint pivot point on the arm peripnery.	Permits a full 180 deg travel with parallel stowage. Segment symmetry.	Maximum reach distance when 3 pitch angles co-linear.
3		Single transition section designed into one arm segment.	Less than 180 deg travel with parallel stowage.	Arm segments non-symmetrical.
4		Off-Set Elbow Joint (Top View)	Greater than 180 deg travel with parallel stowage.	Visual alignment/center line off-set.
5		Dual pivot points with each capable of 90 deg rotation.	Segment symmetry with center line. Parallel stowage.	More complex. Higher weight. Additional control functions.

Figure V-4 Elbow Joint Concepts

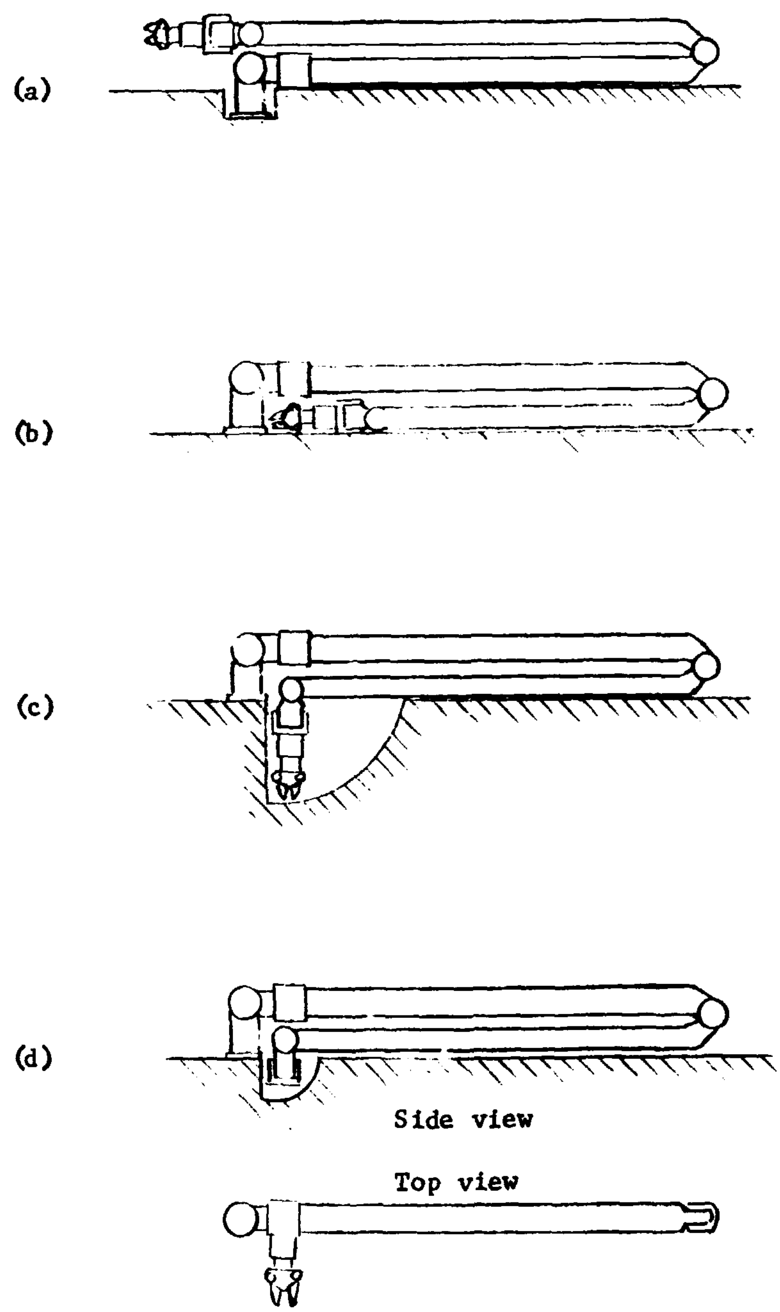


Figure V-5 Stowed Configurations

5. Arm Segment Lengths

A trade study was initiated to establish the effects of having unequal segment lengths for the manipulator upper and lower arms. The primary driving function for considering unequal lengths was based upon the selected arm stowage configuration. In addition, the simplicity of the range, azimuth, and elevation (RAE) control mode which requires a minimum of computational complexity was based upon equal segment lengths and might no longer be applicable to an unequal segment-length manipulator.

Two cases were investigated as illustrated in Fig. V-6. It was assumed that in both cases, the wrist-to-end effector dimension, ℓ_3, would be minimized as this distance does not enhance the working volume of the manipulator, only the overall reach. Based upon the preliminary requirements of a 2.74 m (9.0 ft) reach and a working volume of approximately 2.44 m (8 ft) then,

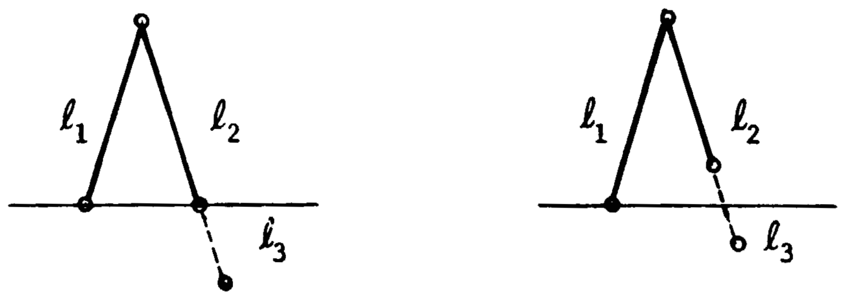
$$\ell_1 + \ell_2 + \ell_3 = 2.74 \text{ m (9 ft) and}$$

$$\ell_1 + \ell_2 \approx 2.44 \text{ m (8 ft)}$$

Note that the sum of $\ell_1 + \ell_2$ is dependent on the final design length required for ℓ_3. Additionally, the primary differences in the two cases is with respect to manipulator control in the range direction, i.e. azimuth and elevation control for each case remains solely a function of the shoulder yaw and pitch gimbals respectively.

Fig. V-7 illustrates the geometric relationship between the arm segment lengths and the manipulator range. In general,

$$R = \ell_1 \cos\alpha + \ell_2 \cos\beta$$



Case I: $\ell_1 = \ell_2$; ℓ_3 minimized

Case II: $\ell_1 > \ell_2$; ℓ_3 minimized

Figure V-6 Equal vs Unequal Arm Segment Lengths

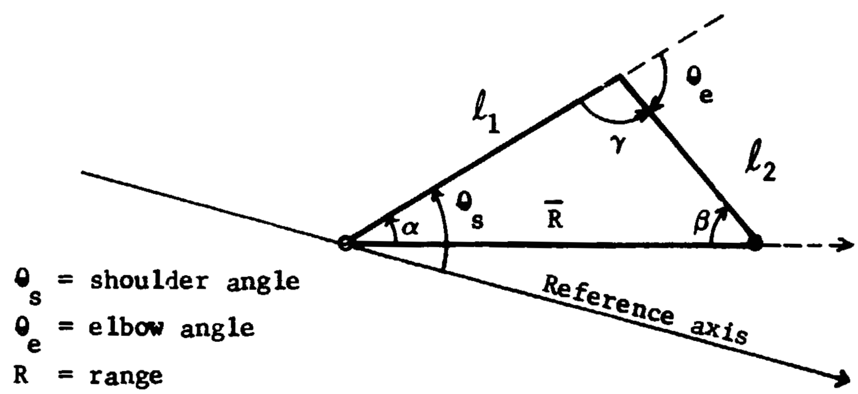


Figure V-7 Generalized Arm Segment Geometric Relationship

where $\alpha = \tan^{-1} \dfrac{\ell_2 \sin\theta_e}{\ell_1 + \ell_2 \cos\theta_e}$

and $\beta = \theta_e - \alpha$

The two cases are initially analyzed where the range vector is defined as the vector from the shoulder gimbal to the wrist pitch gimbal.

a. <u>Case I: $\ell_1 = \ell_2$</u> - For this case, $\ell_1 = \ell_2 = L$ such that the generalized equations may be simplified to

$$R = 2L \cos\alpha$$

where $\alpha = \theta_e/2$

This relationship is shown in Fig. V-8 and illustrates the rather simple geometric relationship provided by using equal segment lengths.

b. Case II; $\ell_1 > \ell_2$ - For this case, the equations may not be simplified. The arm trajectories as a function of range are shown in Fig. V-9. It should be noted that the maximum value of α occurs at 64° or when the range is 55 cm (21.6 in). At this time, any decrease in range results in a decrease in α such that the elbow moves in a "forward" direction, and may in some cases strike the work surface. This, of course, could be prevented through operational procedures.

Additionally, within the 55 cm (21.6 in) range, the angular rate, $\dot{\alpha}$, increases significantly for a constant range rate and the minimum range, given by $\ell_1 - \ell_2$, results in an unreachable sphere of 12.7 cm (5 in.) radius. Therefore, a new technique was investigated to provide complete operational range in a manner similar to that provided by the equal length segment manipulator systems.

Previously, the range vector was defined from the shoulder to the wrist pitch gimbal. If the range vector is defined from the shoulder to a point in space along ℓ_2 such that $\ell_1 = \ell_2 + \Delta$, the manipulator can be controlled in range as though it had equal segment lengths. The manipulator trajectories as a result of this assumption are illustrated in Fig. V-10. These trajectories are well defined and provide for a complete operational range. Thus, control based upon "equal" segment lengths will be used while the actual manipulator will contain unequal lengths based upon the stowage considerations.

6. Joint Torque

The joint torque requirements are based upon both static and dynamic considerations. In general, ground based manipulator systems are

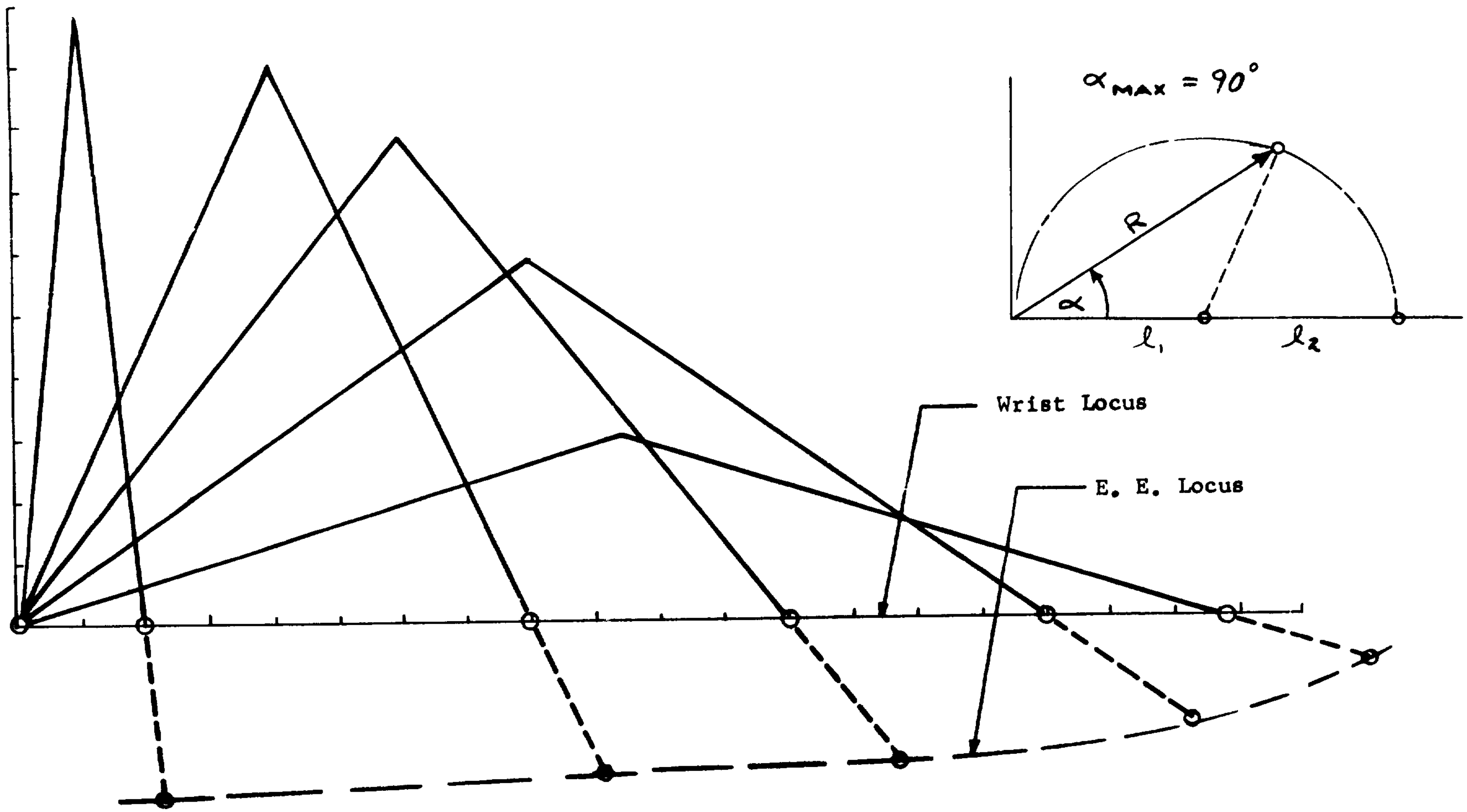


Figure V-8 Equal Length Segment Trajectories

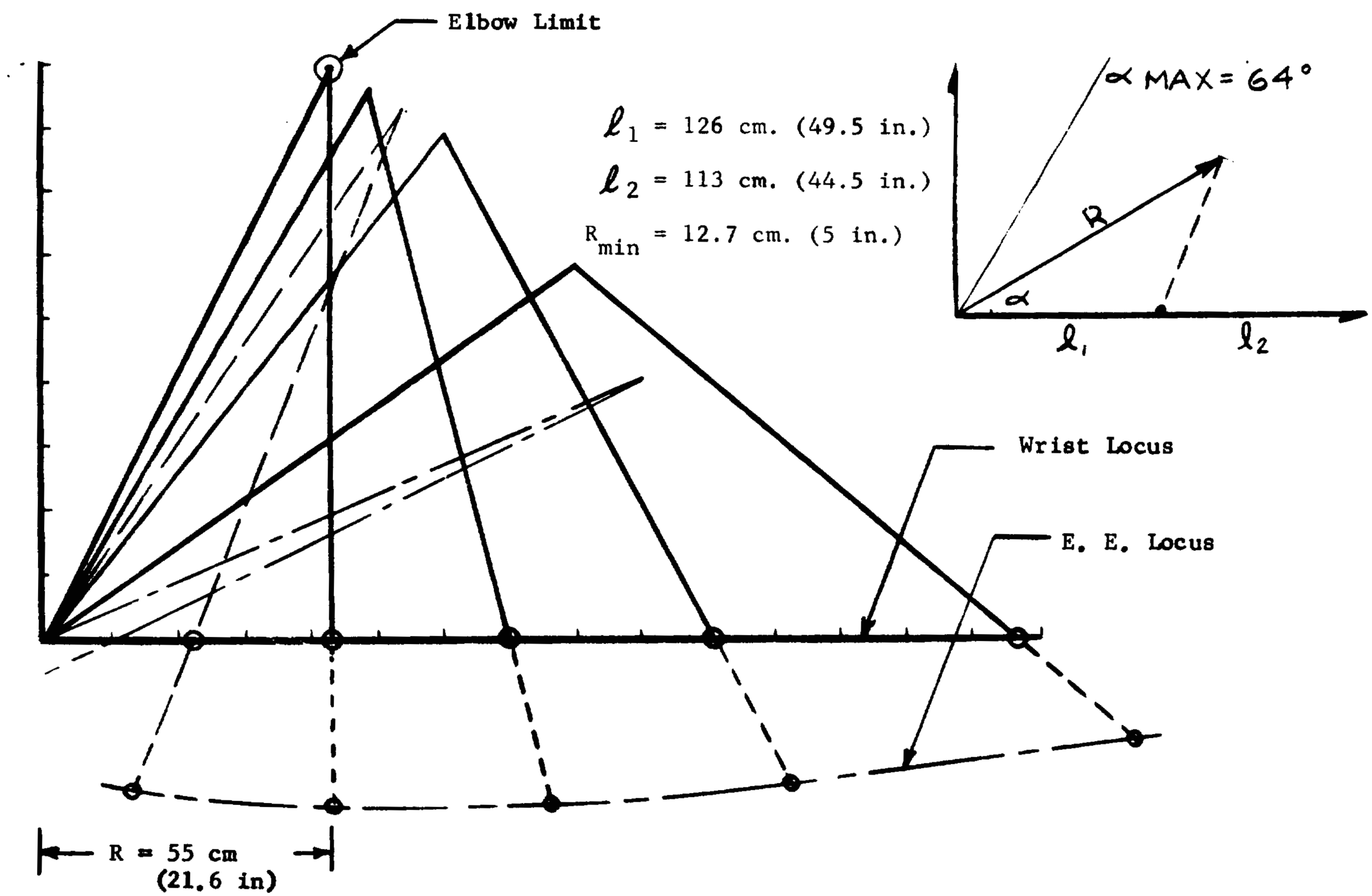


Figure V-9 Unequal Segment Length Trajectories

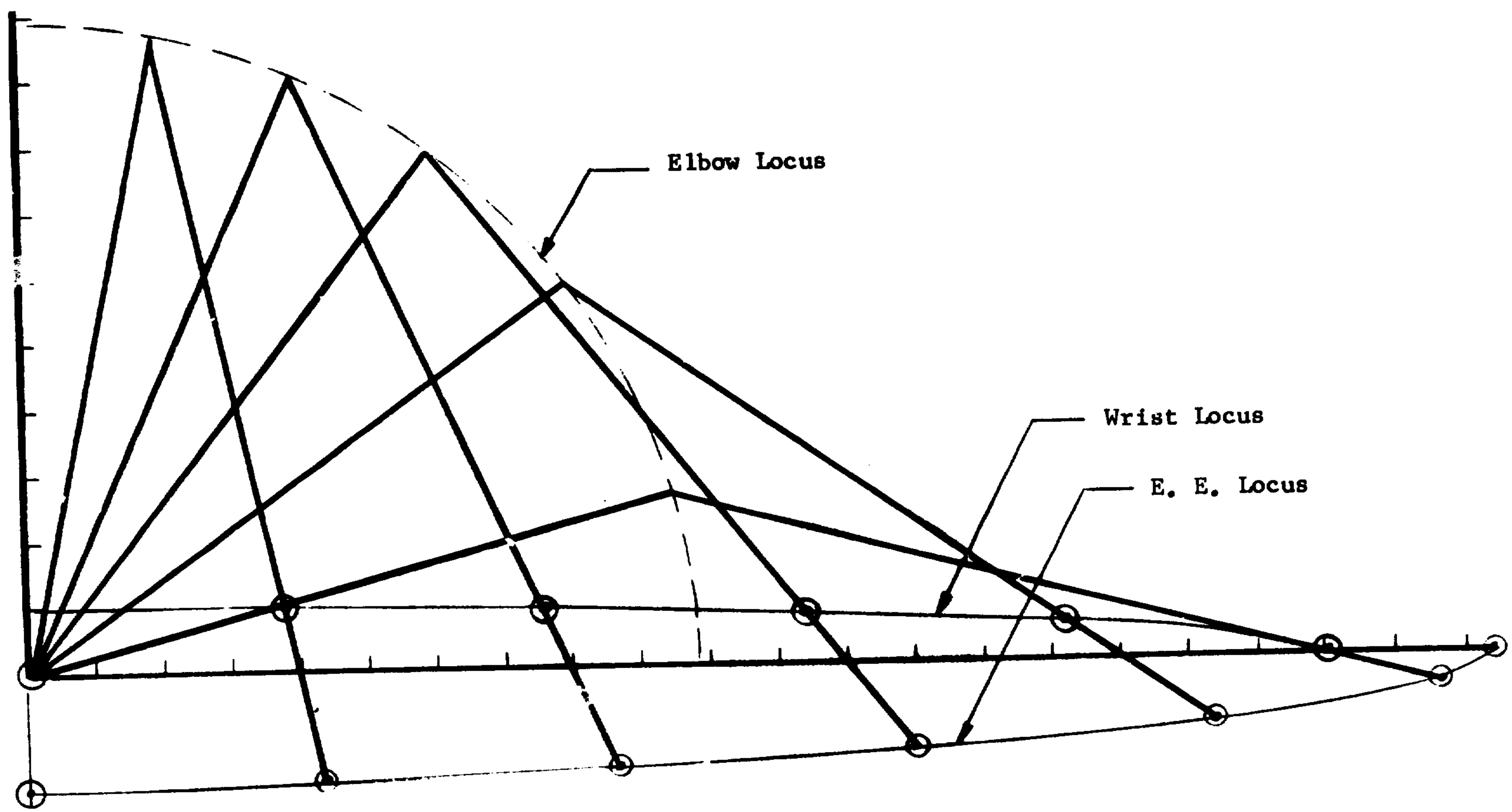


Figure V-10 Alternate Unequal Segment Length Trajectories designed from a static or "tip-force" requirement. The most stringent torque requirement based upon the static case is when the arm is fully extended such that the maximum force is applied at the longest lever arm with respect to the gimbals as shown in Fig. V-11.

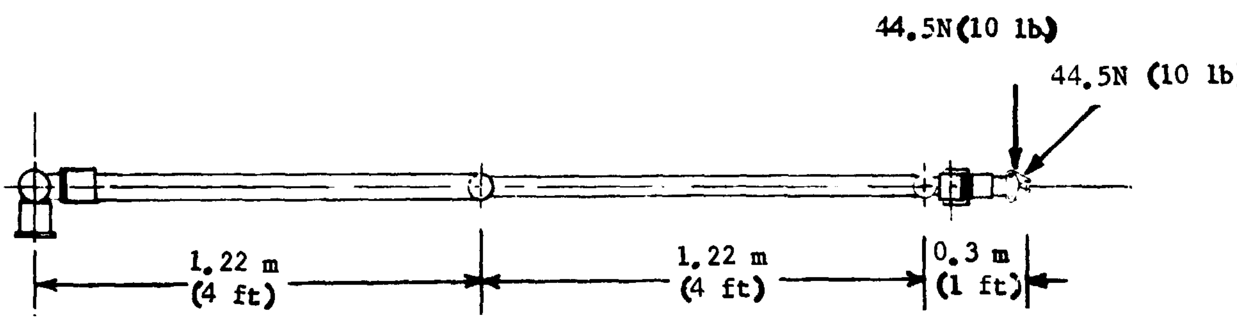


Figure V-11 Static Torques

Based upon the above dimensional information, the static t[illegible]s are given by

$$T_s = F_s \ell$$

where ℓ is the length from the end effector to the applicable joint gimbal.

It is assumed that the yaw-pitch gimbals at the wrist and at the shoulder are concident. Table V-2 summarizes the torques required based solely upon the worst case static considerations.

Table V-2 Static Torques

Gimbals	Torque N-m (ft-lbs)
Shoulder Yaw and Pitch	122.4 (90)
Elbow Pitch	63.0 (50)
Wrist Pitch-Yaw	13.6 (10)
Wrist Roll	20.4 (15*)

* Previously Baselined per Task 2, Preliminary Requirements Analysis

The dynamic torque requirements are primarily a function of the accelerations, or decelerations, required based upon adequate stopping distance and the module transfer velocities, or angular rates, required based primarily upon the time allocation for module transfer.

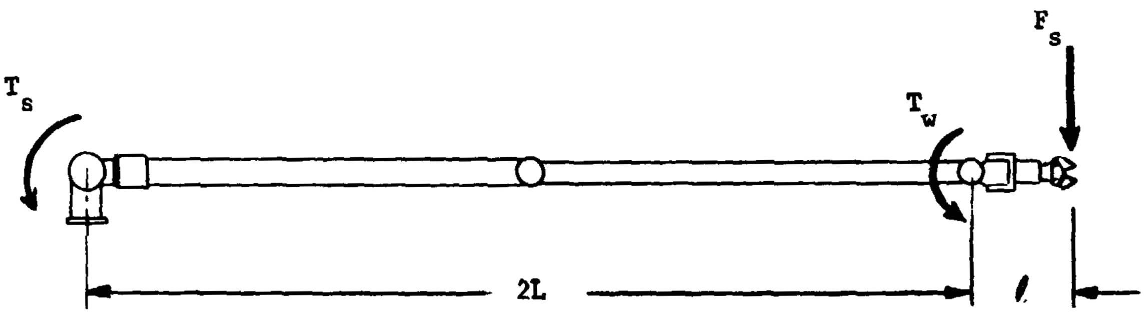
An analysis was conducted to establish the dynamic effects of the manipulator system from the unloaded to the maximum loaded case. The analysis, contained in Appendix B, shows a significant amount of attention must be given to the dynamic torque requirements for manipulator systems operating in a zero gravity environment. One important conclusion resulting from this analysis is that if the manipulator system is designed solely from static considerations, then the manipulator wrist becomes a "weak link" in the system. A simple example ignoring manipulator mass/inertia and module inertia, illustrates this "weak link" at the wrist.

With reference to Fig. V-12, from static considerations the manipulator shoulder torques required are 122 N-m (90 ft-lbs) and the wrist torques required are 13.6 N-m (10 ft-lbs).

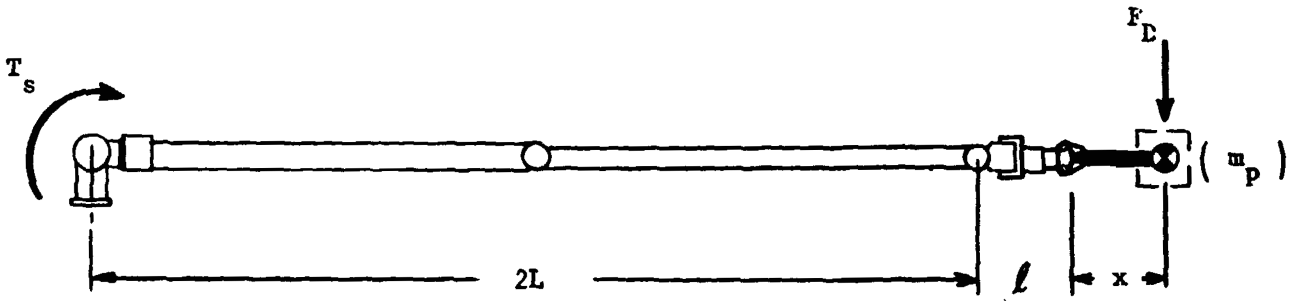
Now, assume the maximum shoulder torque available is used to accelerate a 146 Kg (10 slug) module. The apparent force acting on the module, from Fig. V-12, is 40 N (9 lbs) and the torque required by the wrist becomes 24.5 N-m (18 ft-lbs) or nearly twice that required from static considerations.

Thus the designer is confronted with three options that are available to provide an arm with adequate dynamic strength. These include: (1) increase the torque capability of the wrist; (2) operate the wrist in conjunction with brakes; or (3) limit the shoulder/elbow torques when handling large payloads.

Recognizing that the manipulator design will incorporate brakes as a safety measure in the event of a power loss and, in addition, commonality



$$T_s = F_s\ (2L + \ell);\quad T_\omega = F_s \ell$$



$$F_D = m_p \alpha\ (2L + \ell + x) \qquad T_\omega = F_D\ (\ell + x)$$

$$\alpha = T_s/I = T_s/m_p\ (2L + \ell + x)^2$$

Assumptions:

$2L = 2.4$ m (8 ft)

$\ell = 0.3$ m (1 ft)

$x = 0.3$ m (1 ft)

$m_p = 146$ Kg (10 slugs)

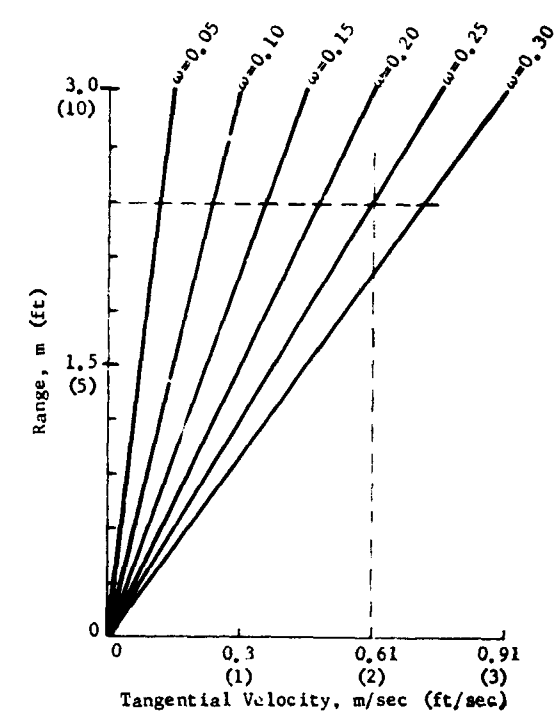
Figure V-12 Static vs Dynamic Torques

within the overall wrist design is desirable, the wrist pitch and yaw torques were increased to 20.4 N-m (15 ft-lbs). This torque when coupled with the brake provides a 40.8 N-m (30 ft-lbs) wrist torque capability which is more than adequate for the largest serviceable module.

Joint Angular Rates

a. Typical Operational Rates - The manipulator operational rates are based upon two considerations: (1) provide rates such that task times are reasonable and (2) assure stopping distances, with respect to the maximum rates and module masses, are not excessive.

Fig. V-13 illustrates the interrelationship between the shoulder angular rates, tip tangential velocities, and time to complete a 180° rotational maneuver. The preliminary requirements analysis (Task 2) established a maximum tip velocity of ≤0.61 m/sec (2 ft/sec). A task time of 10-20



Time for 180° rotation at ω_{max}

ω (rad/sec)	t sec
0.05	62.8
0.10	31.4
0.15	20.9
0.20	15.7
0.25	12.5
0.30	10.5

Figure V-13 Shoulder Rates

seconds, not including acceleration/deceleration time was assumed adequate for a 180° rotation. From the curves, shoulder rates of 0.2 rad/sec (11.5°/sec) were selected as the nominal maximum operational rates. From manipulator geometry considerations, the remaining joint rates were established as summarized in Table V-3.

Table V-3 Joint Angular Rates

Shoulder Yaw:	0.2 r/s	Wrist Pitch:	0.2 r/s
Shoulder Pitch:	0.2 r/s	Wrist Yaw:	0.2 r/s
Elbow Pitch:	0.4 r/s	Wrist Roll:	0.2 r/s

b. Centrifugal Force - Prior to baselining the joint angular rates, the centrifugal force developed on the arm was investigated assuming the maximum manipulator reach and angular velocity and the largest module mass. The results, shown graphically in Fig. V-14, indicate the magnitudes are within the "strength" capability of the manipulator.

c. Stopping Distances - The stopping distance, again under "worst case" conditions was established as under 0.52 m (1.7 ft) as shown in Fig. V-15. However, it should be noted that in general the largest module will be transferred at rates less than the maximum available by the manipulator and therefore shorter stopping distances are more realistic.

d. Tip Translational Rates - Two control techniques are commonly proposed for manipulator application: (1) joint rate control in which the gimbals are driven at a commanded angular rate and (2) tip translational control in which the manipulator tip is driven at a commanded linear velocity. The manipulator tip translational rates, based upon the selected joint angular rates, are shown in Fig. V-16.

In the case of tip translational velocity control, the operating range is limited unless the maximum allowable gimbal rates are increased.

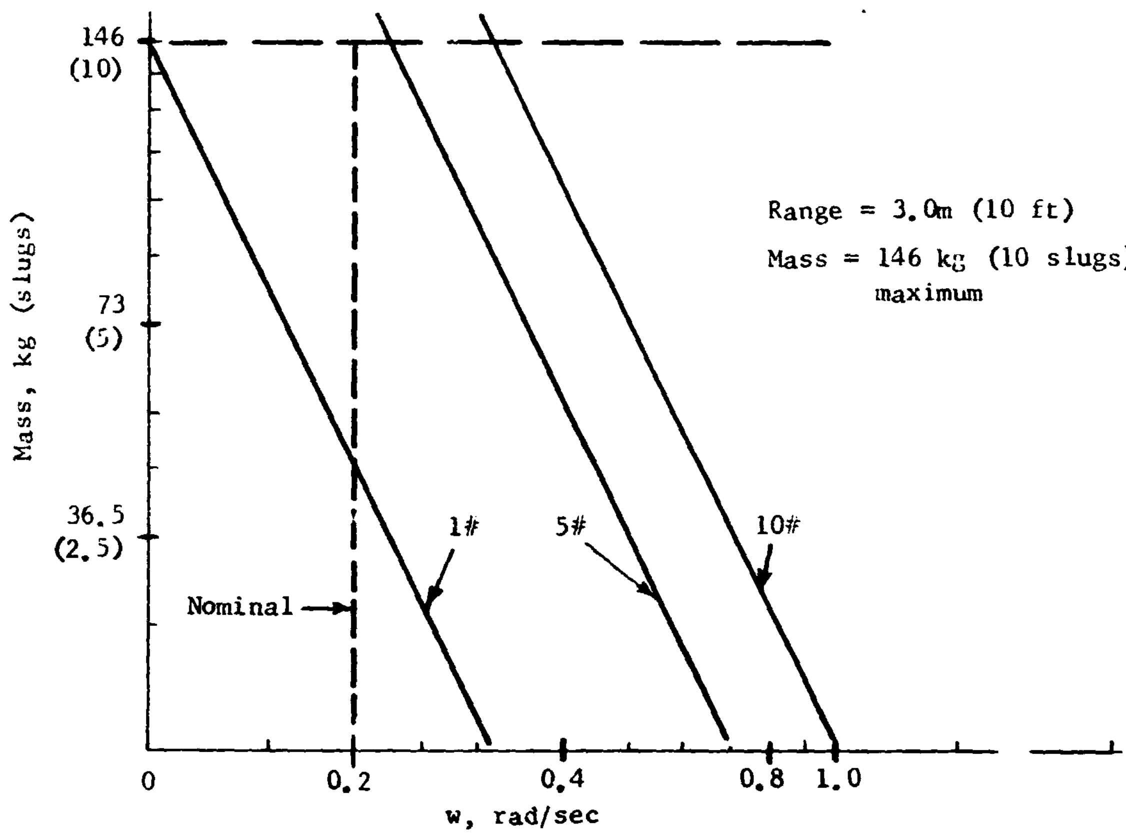


Figure V-14 Centrifugal Forces

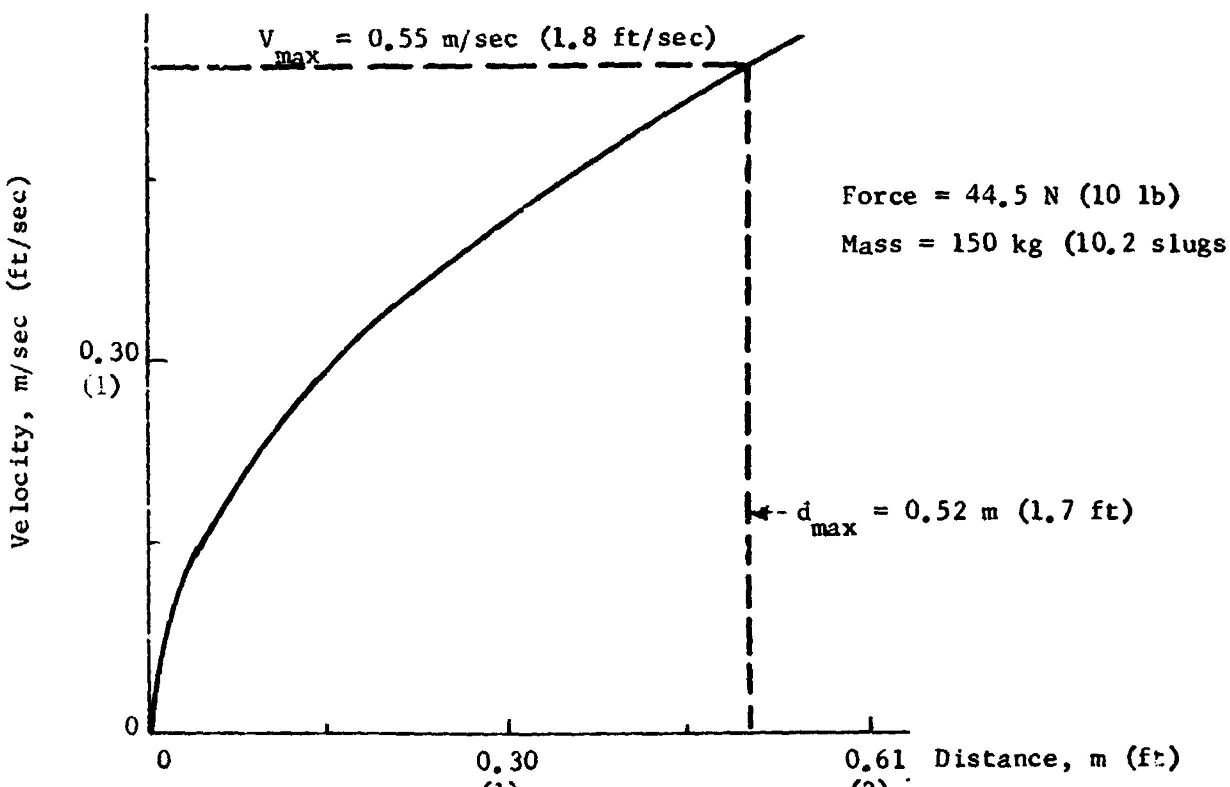


Figure V-15 Worst Case Stopping Distances

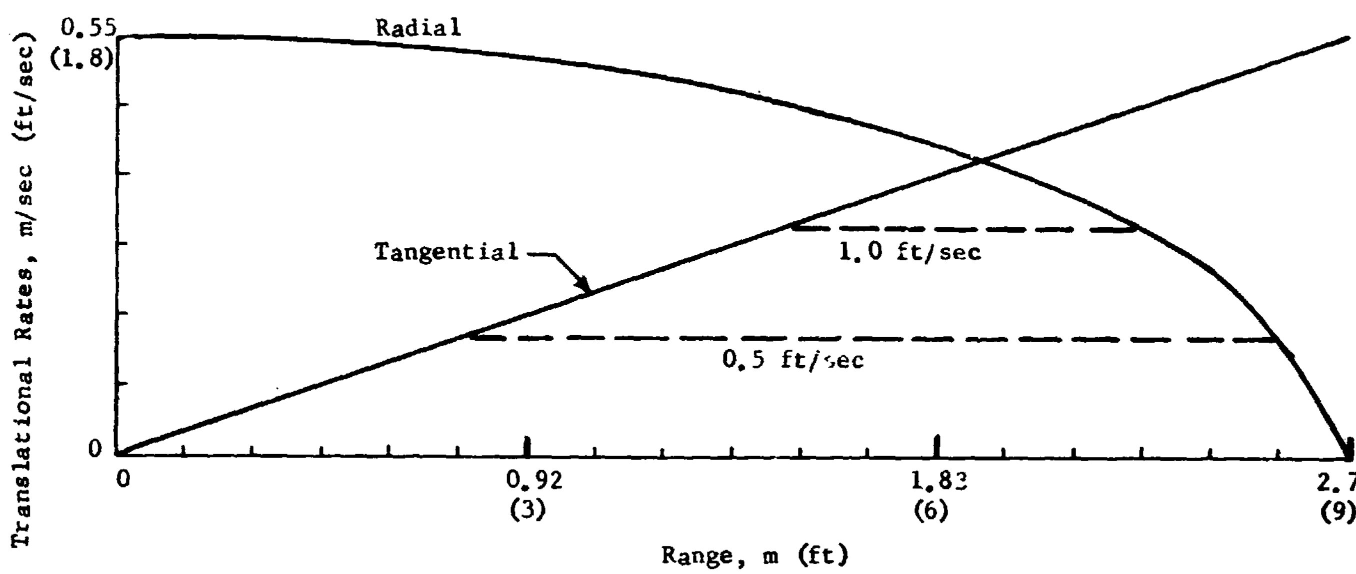


Figure V-16. Radial and Tangential Rates

For example, since R = 2L cos α, the range rate $\dot{R} = -2L \sin \alpha \ \dot{\alpha}$ and as $\alpha \longrightarrow \pi/2$ the gimbal rates must be increased significantly to maintain a constant range rate. However, a wide operating range is available before this occurs. The primary limitation arises from tangential velocity considerations (i.e., maximum shoulder rotational rates). While joint rate control is simpler to implement, the final choice must be based upon operator preference or performance.

B. STRUCTURAL ANALYSIS

1. Square vs Circular Arm Segment Cross-Section

Because of the consideration of minimum weight in the design of the manipulator arm, various shaped cross-sections were studied. The two most common shapes selected for more detailed evaluations were:

a. The thin wall round tube for a 3" to 4" diametric range with $50 \leq \frac{D}{t} \leq 100$ where D = outside diameter and t = wall thickness

b. The thin wall square tube for a 3" to 4" square range with $50 \leq \frac{W}{h} \leq 100$ where w = outside width and h = wall thickness

Both of these tubes have advantages and disadvantages and were evaluated in terms of the following characteristics: bending, torsion, volume, and design considerations.

a. Bending - The two different shapes of structural members were compared against each other while maintaining the same mass per unit length properties. The simplified area moment of inertia formula for the thin walled circular tubing is

$$I_c = \pi \frac{D^3}{8} t$$

where D is the average diameter of the tube and t is the wall thickness.

The area moment of inertia for square tubing is

$$I_s = \frac{D^4}{12} - \frac{(D-2h)^4}{12}$$

where h is the wall thickness of square tubing.

For the same weight per unit-length of tubes, the cross-sectional areas must be identical. Thus,

$$A_{CIRC.\ TUBE} = A_{SQUARE\ TUBE}$$

$$2\pi \frac{D}{2} t = 4\ (D-h)h$$

$$t = \frac{4}{\pi} h$$

The two area moments of inertias are

$$I_c = \frac{D^3 h}{2}$$

$$I_s = \frac{D^4}{12} - \frac{(D-2h)^4}{12}$$

Fig. V-17 compares these two expressions based upon

$$\%\ INCREASE = \frac{I_{SQUARE} - I_{CIRCULAR}}{I_{CIRCULAR}} \times 100$$

and shows the variation of inertia increase of a square tube with respect to a circular tube as a function of wall thickness. The practical range is indicated as the curves beyond wall thickness of 0.3 cm should be ignored because the thin wall formula does not apply to the circular cross-section for the specified ranges of diameter. On the other hand, the tube becomes impractical to manufacture when wall thickness is under 0.1 cm.

b. Torsional Resistance - Although the torsional shear stress (τ) will occur simultaneously with the bending stress, the shear stresses for square and round tubing were evaluated as a separate item. The shear stress is given by

$$\tau = \frac{T}{2At}$$

and identical torques (T) will be applied to both tubes. The respective tube areas (A) are

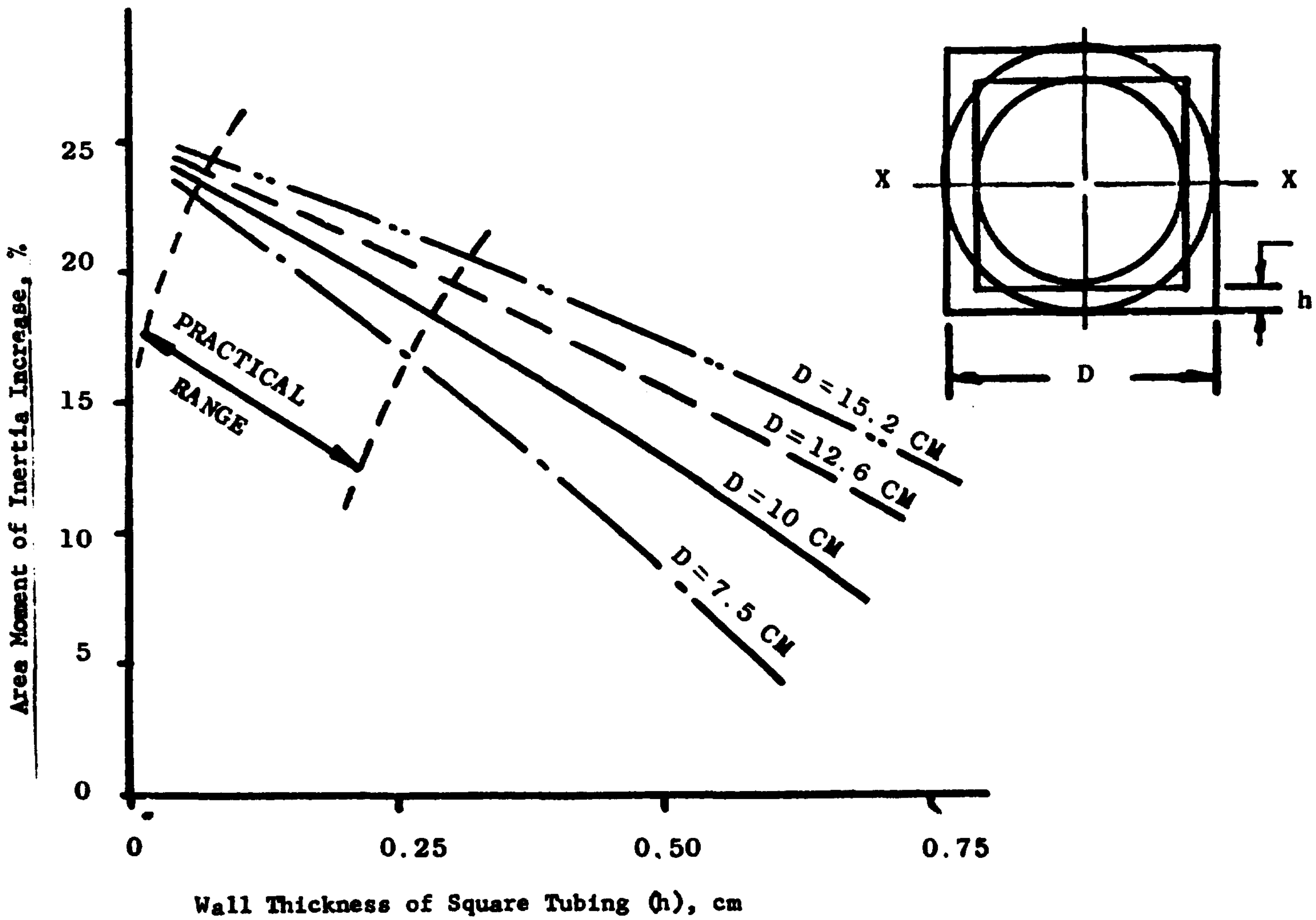


Figure V-17 Inertia Variations: Square vs Circular Tubes

$$A_{CIR} = \frac{\pi D^2}{4}$$

$$A_{SQUARE} = D^2$$

Again, to achieve identical mass per unit lengths, the wall thicknesses (t) must be adjusted. Let h be the thickness of the square tube. Then,

$$t = \frac{4}{\pi} h$$

so $$\tau_{CIRCLE} = \frac{T}{2D^2 h}$$

$$\tau_{SQUARE} = \frac{T}{2D^2 h}$$

The shear stress resistance of each tube is identical when their weight/unit length and diameters are the same. However, it must be pointed out that the stress concentration factor (k), to be applied to the resulting shear stress, occurs in the case of a square tube. The fillet radius (r) at the inner corners of a square cross-section of the tube will influence the maximum shear stress. For a round tube, $k = 1$.

The stress concentration factor according to S. Timoshenko in Strength of Materials, Part II is: $k = 1.74 \sqrt[3]{\frac{h}{r}}$.

Therefore, an important requirement is that the fillet radius of square tube be larger or equal to the wall thickness, i.e., $r \geq h$. Then $k \approx 1.74$ can be used as a multiplication factor for shear stress.

In order to point out the approximate size of this stress the worst case condition of a 3 meter manipulator arm will be considered as an example. When

$D = 10$ cm

$h = .125$ cm

$T = 60$ newton-meters

Then $\quad \tau = 1.74 \dfrac{T}{2Ah} = 406 \ N/cm^2 \ (\sim 590 \ psi)$

which is small compared to the strength of aluminum alloy. Furthermore when this maximum shear stress occurs the bending stress is at its minimum level.

c. Volumetric Considerations - The width of the square tube is identical to the diameter of the round tube. Therefore, the square tube will occupy 21% more volume than the round tube. However investigation of the FFTS system shows that the square tube has advantages in stowage and the volume increase of the arm does not interfere with the performance of the FFTS.

d. Design Considerations - Experience with both types of tubes indicates that the design call outs, mountings, jointing, and manufacturing can more easily be achieved with square tubing. Drive assemblies at shoulder, elbow, and wrist must be blended into the tubular portion of the arm for good design practice, and this can be achieved with square tubing quite satisfactorily.

The extruded square tube will be modified by an end mill process. Each of the four sides of the tube must be cut to the required thickness. Compared to round tube, the square tube is much harder to finish on the inside. Therefore all wall modifications will be done only on the outside. However, angular orientation and synchronization of pin or screw holes at both ends of a square tube is an easier process.

Therefore, the square tubing is recommended for the arm segment portions of the manipulator arm.

2. <u>Material Selection</u>

Materials to be used in the construction of structural and supporting elements require the evaluation of the many different materials available in the commercial market from the following points of view: Density (ρ); strength (tension, S_T, compression); flexural rigidity (E); coefficient of thermal expansion (C_T); size (space consideration); cost; and manufacturing technique available.

Table V-4 gives the properties and characteristics of candidate materials to be used in the design of the FFTS manipulator arm.

Table V-4 Properties of Candidate Materials

Material	E PSI $\times 10^{-6}$	ρ Lb/In^3	E/ρ Inch $\times 10^{-6}$	S_T PSI $\times 10^{-3}$	C_T Per °C $\times 10^6$	C_p Thermal Capacity BTU/Lb°F	K Thermal Conductivity BTU/Hr Ft°F	Installed Cost (Relative)
6061-T6 Aluminum	10	.10	100	35	23	.20	90	10
Beryllium	42	.07	600	40	10	.40	87	1000
Epoxy	.5	.045	11					150
Graphite Epoxy	20	.054	370		3			200
Invar	30	.075	100	100	1.5	.11		10
Lockalloy	28	.16	374	40	~ 15	~.3	~ 85	500
52100 Steel	30	.30	100	150	10	.11	25	10
Stainless 440 Steel	30	.30	100	150	10	.11	10	10
Titanium	17	.16	109	150	9	.13	4	35

a. Material Tradeoffs of Tubular Extension - Structural elements such as tubes can be built by overwrapping many layers of epoxy/glastape which has interwoven high strength filaments of boron or graphite, to form the thin wall shape desired. Afterward a cure process bonds the assembly together. The tube assembly can be given an isotropic strength by crosswrapping in 45° direction. This tube has good strength-to-weight ratio.

Comparing the coefficient of thermal expansion for metals and epoxy composites, the suitable combination would be a boron epoxy wrapover on thin wall titanium tube. Thermal analysis shows that under differential temperature condition the wrap is larger for boron epoxy material than the graphite epoxy. Therefore, among epoxy materials the graphite epoxy is the better choice for tubular structure as it is applied to the FFTS manipulator arm. The technique of making graphite epoxy st[illegible]tures has been developed by Martin Marietta Corporation in connec[illegible] with the "Lunar Surface Drill" program. The Lockalloy material do[illegible] provide the superior stiffness-to-weight ratio as does beryllium or graphite epoxy. However, it can be machined quite easily with post cutting treatment for minute stress cracks required. The poorest in performance aspects among candidate structural materials for constructing arm extensions is the aluminum. However, it has other good characteristics. Besides its low price the aluminum has high thermal conductivity and the thermal stabilization of the tube can occur very rapidly. Therefore, the graphite epoxy is recommended with an insulated aluminum tubing as an alternate.

b. Joint Housing Materials - A similar comparison could be made for the materials used for joint housing. However, other factors enter the picture. Epoxy composites are not well suited to the fabrication of precision parts. Cutting through fibers wrapped for strength may derate the load carrying capability. The housing contains gears and the outer races of the bearings which are made out of steel material. Looking at the thermal contraction or expansion aspects of the titanium material it looks most feasible to use titanium for housing and bracketry.

Although titanium is a poor heat conductor, it will contract and expand with about the same rate as steel, so that no considerable differential dimension accumulations can occur. Furthermore, the titanium has good strength to weight ratio and can be machined.

c. <u>Motor-Generator Housing</u> - Due to the [illegible] heat rise problems of the motor-rotor under high temperature envir[illegible] (200°F) one must use a material which has a high thermal conduct[illegible] and high, thermal capacity. There are three materials listed in Table V-4 which has high thermal conductivity: aluminum, beryllium and Lockalloy. Beryllium looks the most desirable material, however, its fabrication and cost will make its use questionable as well as Lockalloy. Therefore, the aluminum housing for motors is the best choice.

d. <u>Gears</u> - From lubrication point of view, the choice of material for pinions and gears is reduced to stainless steel. Stainless steel 440 can be hardened and cut quite routinely and no problems are foreseen during the fabrication of this steel. The gear materials will have somewhat lower hardness requirements and therefore 17-4PH-H-900 type of stainless steel is recommended.

At this point however one must mention the possibility of cutting the gears out of titanium. With an excellent lubricant available, the titanium gears not only make the joint weights lighter but their load carrying capability is increased from the contact stress point of view. The lubricant available for this is the so-called "canadizing" R by General Magnaplat Corporation.

Table V-5 summarizes the selected and possible material for FFTS manipulator arm.

Table V-5 Material(s) Selection Summary

Material / Application	6061-T6 Aluminum	Beryllium	Boron Epoxy	Graphite Epoxy	Lockalloy	(52100) Steel	CRS (Stainless)	Titanium
Tube Extensions	Alternate	Possible	--	Selected	--	--	--	--
Gear Housings	Possible	--	--	--	--	--	Possible	Selected
Gear Shaft Supports	Possible	--	--	--	--	--	Possible	Selected
Motor-Gen Housing	Selected	Possible	--	--	Possible	--	--	--
Bearings	--	--	--	--	--	Selected	Selected	--
Gears	--	--	--	--	--	--	Selected	Possible
Pinions with Shafts	--	--	--	--	--	--	Selected	Possible
Fabrication Development	Excellent None	Poor Small	Average High	Moderate Small/None	Good Small	Excellent None	Excellent None	Moderate None

3. Deflection and Vibration Considerations

An analysis of the manipulator deflection and vibration characteristics was conducted based upon the preliminary mass properties of the manipulator. The analysis is contained in Appendix C and indicates the maximum tip deflection of the arm under a 44.5 N (10 lb) load is less than 0.84 cm (0.33 in).

The natural frequencies of the manipulator ranged from 0.97 hz for the loaded arm (300 lb module) to 3.9 hz for the unloaded arm. It was noted in Appendix C that in order to increase the natural frequency to 6 hz, such that operator command inputs will not excite resonance, the arm must be made about 39 times as stiff, an unattractive solution. However, the manipulator arm is backdriveable. Therefore, when the tip force exceeds some nominal value such that the joints backdrive, kinetic energy of the system will be absorbed and the vibrations reduced. As a result of this arm characteristic, it is recommended a more complete analysis be carried out rather than attempting to excessively stiffen the arm.

C. ACTUATOR ANALYSIS

1. Motors

An analysis was conducted on motors for application to the FFTS manipulator system. This analysis, contained in Appendix D, establishes the selection of permanent magnet dc torquers.

Both the brush and brushless techniques were considered to reveal the advantages and disadvantages of both methods. The primary reason for development of the brushless approach was to relieve the problem of finite brush life. The price paid for brush removal is added system weight and electronic complexity.

The following considerations reveal the reasoning behind the initial selection of brush type torque motors.

Brush Life

Two principle factors governing brush duration are the type of lubrication used and the total linear distance the commutator travels under the brush. Average wear statistics reveal brushes subjected to a wet lubricant disintegrate at a 10^{-12} cm^3/in rate (oil vapor pressure atmosphere) while those operating in a dry condition deteriate at a faster 10^{-9} cm^3/in rate (hard vacuum). For a continuous rotation application, such as a momentum wheel, long life operation (5-20 years) is prevented by eventual brush failure. For the FFTS manipulator, continuous high speed operation does not occur and the mission lifetime is comparatively short (100 hrs). Lacking specific total motor revolution figures, consider the following as a plausible worst case condition. Suppose the manipulator shoulder pitch gimbal rotated continuously at 0.2 rad/sec for 25 hours. Assuming a 3.5 inch diameter motor and a 50:1 gear ratio, the total linear distance (S_c) traveled by the commutator is:

$$S_c = (0.2 \text{ rad/sec}) \left(\frac{3600 \text{ sec}}{\text{hr}}\right) (25 \text{ hrs}) \left(\frac{3.5 \text{ inches}}{2}\right) (50) = 1.58 \times 10^6 \text{ inch,}$$

giving rise to 1.58×10^{-6} cm^3 and 1.58×10^{-3} cm^3 deteriation for wet and dry lubricated commutators, respectively. Assuming a 30×10^{-3} cm^3 brush volume (appropriate for a 120 in-oz dc torquer), 5×10^{-3}% and 5% of total brush volume is used for the wet and dry lubricated situations.

Although these estimated brush life values represent only a plausible argument, they do indicate the feasibility of using brush commutation for the manipulator gimbal actuators.

Temperature

The environment temperature effects upon the actuator assembly and the motor generated heat transfer into the housing structure must be considered in the motor type selection. The brush type torquer, designed to functionally operate in a ± 200°C environment, is not seriously restricted by the large temperature variations. Although the armature and rotor assemblies of the brushless design likewise can withstand the temperature extremes, the associated switching and commutation electronics must be temperature protected. This protection would require the electronics for all gimbals to be placed in the free flyer, or else incorporate heaters in each actuator housing.

In contrast to the disadvantage of the brushless torquer electronics, the inverted design does facilitate heat transfer from the stationary armature to the support structure. Dissipation of armature produced heat in the brush torquer is more difficult in that the armature rotates and thus a shaft and bearings form the conduction path to the housing structure.

Noise

Although generated RFI/EMI brush noise is eliminated with a brushless torquer, switching transients are introduced if a square wave drive is utilized.

Shaft Power

Commutation problems in a brush motor limit the allowable shaft power to approximately one-fourth the maximum input power. This limitation is relieved with a brushless design, permitting a larger shaft power to maximum input power ratio - the ratio magnitude being limited by the switching electronics.

Wires

Since the manipulator has articulated gimbals, the wire routing to the lower actuators presents a formidable challenge when the wire count becomes large. Whereas two wires are needed to activate a brush motor, from six to thirty conductors are required for a brushless torquer if the switching electronics are removed from the motor vicinity.

Based upon the above advantages and disadvantages of the two motor types, and considering system complexity and cost, the brush, permanent magnet, dc torquer with a dry lubricant* was initially selected for the manipulator gimbal actuators.

Table V-6 summarizes the actuator Input/Output Criteria established to date.

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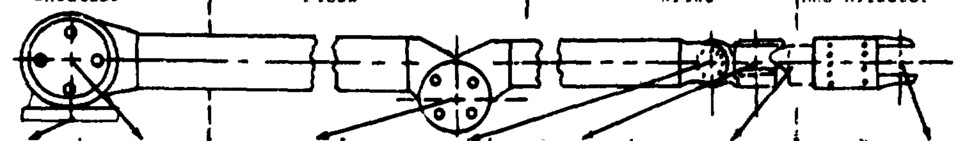
* Note: Later analysis identified a solid lubricant as preferable over the dry type.

Table V-6 Actuator Input/Output Criteria



Joint Locations / Characteristics	Seven Degree-of-freedom Manipulator						
	Shoulder		Elbow		Wrist		End Effector
Joints and Motions	Yaw	Pitch	Pitch	Pitch	Yaw	Roll	Gripper
Joint Outputs:							
Tc que, N-M (Ft-lb)	123 (90)	123 (90)	68 (50)	20,5 (15)	20,5 (15)	20,5 (15)	44-89 N (10-20 lb)
Travel, rad (deg)	3,5 (±200)	3,2 (180)	3,2 (180)	1,6 (90)	±1,5 (±85)	Continuous	7,6 cm (3 in.)
Speed: rad/sec (deg/sec)							
Loaded	0,2 (11,5)	0,2 (11,5)	0,4 (23)	0,2 (11,5)	0,2 (11,5)	0,2 (11,5)	N/A
Unloaded							(2 ips)
Stopping Dis. rad (deg)							
Loaded	0,22 (13)	0,22 (13)	TBD	TBD	TBD	TBD	N/A
Unloaded							
Joint Inputs:							
Backlash, arc-sec	6	6	6	6	6	6	2
Backdriveable	Yes	Yes	Yes	Yes	Yes	Yes	No
Friction, Gear Train	Min	Min	Min	Min	Min	Min	High
Friction, Motor	Min	Min	Min	Min	Min	Min	NC
Brakes							No
Duty Cycle, Time/cycle (sec)	30	30	30	30	30	30	10
Accum. Time/Hr)	25	25	25	25	25	25	10
Imposed Design Factors:							
Control Schm (Rate-Rate)	Tach	Tach	Pot & Tach	Tach	Tach	Tach	Tach
Rate-Rate with Hawk	Tach	Pot & Tach	Pot & Tach	Pot & Tach	Pot & Tach	Pot & Tach	Tach
Response Time	NC	NC	NC	NC	NC	NC	N/A
Speed Var.	NC	NC	NC	NC	NC	NC	N/A
Man-Machine							
Response Time (sec)	NC	NC	NC	NC	NC	NC	N/A
Work Element Time	TBD	TBD	TBD	TBD	TBD	TBD	2 sec.

2. Joint Drive (Gear System) Selection Considerations

There are numerous points of view and considerations when one tries to select the right gear system for a specific application. In the case of the manipulator arm the ideal situation would be to have no gears at all but to use only the dc torquers to do angular displacements of the arm segments which would increase the weight of the arm 15-20 fold and would be an impractical tool for space application. A drive assembly consists of a motor and a gear train and for a specified torque output, will have an optimum gear ratio range. As a rule of thumb and considering the preliminary candidate design, under a 25:1 gear ratio the motor weight starts to be the dominant weight factor. Above 150:1 the gear-supporting structure starts to dominate the weight of the drive assembly.

a. Limitations and Characteristics of Gears - There are numerous ways one can transfer motion and force (torque) from one machine element to the other (i.e., from an electric motor to a manipulator arm), including belt drives, friction drives, linkages, cams and all elements which have constrained motions.

Each of the above machine elements has its own merits with respect to any characterized application. When the requirements call for a specific velocity, acceleration, forward and backward motion of the system, and a high degree of controllable angular accuracy, the choice will be a gear train. Their major function is to alter the mechanical work supplied to them into a logical predetermined rotation and twisting moment (torque). Therefore, gears and gear trains as power transmitting devices were considered for the manipulator arm joints.

The individual gear meshes must be provided with backlash in order to provide a smooth driving condition for the gear system, based upon the thermal variations anticipated in the space environment. The amount of backlash depends not only on the design and manufacturing conditions, but on environmental conditions as well. The sources of backlash from the points of view of design and manufacturing are fixed magnitude (e.g., tooth size of gear, actual center distance with respect to ideal, shafts and bearings radial clearances) and variable magnitude (e.g., the total composite error in gear, ball bearings eccentricity, shafts run outs, and eccentricity between gear bore and shaft diameter).

One additional area to be considered in the actuator joint design is backdrivability.

Under normal operating conditions, the load-carrying manipulator arm will be controlled by the torque motors located in the joints. When failure occurs with use of a non-backdriving gear system and the electric current supply ceases to function, the motor will stall and be unable to execute a gradual stop. The forces created by the sudden deceleration will exert a very high impact load on the gears and the manipulator structure as illustrated in Fig. V-18. However, if the joints are backdrivable, friction brakes can be incorporated which engage when deenergized and gradually stop the mass motion. The system will stay safe and no hazard can occur to surrounding objects or to the structure of the manipulator itself. Fig. V-18 indicates the safe velocities for a 300 lb object under various stiffness conditions of the manipulator arm. The kinetic energy of the load and manipulator arm was equated with the strain energy of the arm. It can be seen that the stiffer the arm, the higher the load will be on the gear teeth. Therefore, this manipulator arm would become large and heavy in size and would be an impractical space tool. It can also be concluded here that it is mandatory to have a sound gear system free of cogging and breakage possibilities.

b. <u>Gear Train Requirements of FFTS</u> - The following is a list of baselined gear train requirements:

High consistent efficiency either as speed reducer or as a speed increaser (backdrive).

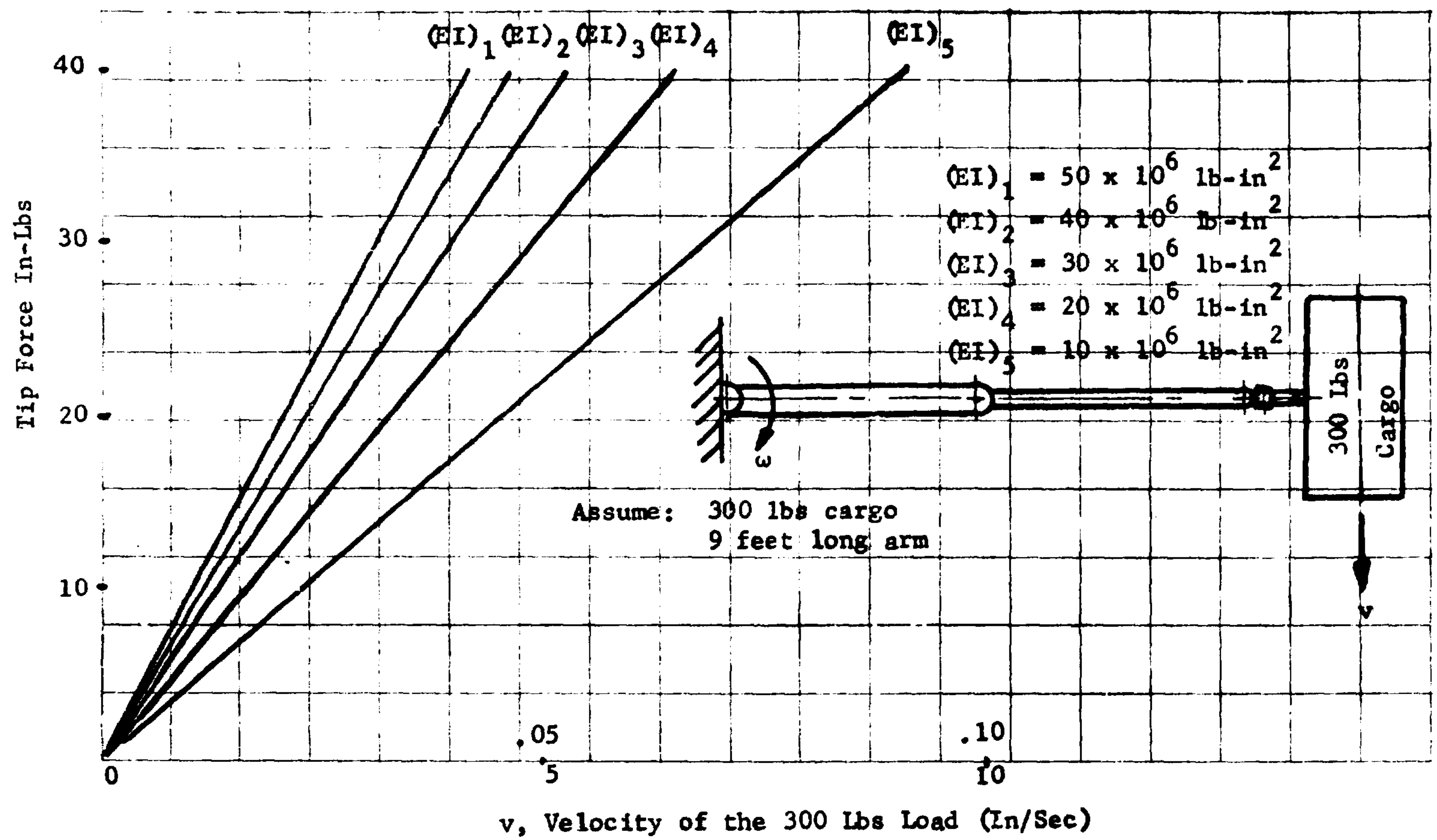


Figure V-18 Safe Manipulator Velocities

- Minimum backlash (control and accuracy requirement).
- Light and compact design.
- Minimum or no windup between input and output shafts, caused by bearing deflection, shaft torsion, tooth deflection, etc. (accuracy and control requirement).
- Able to contract and expand under extremes of temperatures.
- Gears and bearings must be permanently lubricated.
- Material selection:
  - Minimize outgassing
  - Avoid stress and surface corrosion.

c. Gear Designs Considered - The following gear systems were considered for the manipulator actuator.

(1) Dual Gear Train with Spring Loaded Drive Pinion - The classic way to eliminate backlash, and it is a simple concept. Two independent gear reduction paths drive one internal ring gear from a spring loaded pinion. A single motor is required as shown in Fig. V-19. The low efficiency of this system is its major drawback. While one gear train is driving, the other train forces against the reverse side of the involute gear teeth. An extra amount of sliding friction is created and it adds to the power losses of the joint. The estimated efficiency of this system is about 50%.

(2) Dual Gear Train with Independent Motors - Same as above, but each of the two gear paths has separate drive motors as shown in Fig. V-20. One motor drives in one direction while the other motor gives way to the motion holding a predetermined stall torque in the other direction (reverse side of the tooth). For the reverse motion of the output gear, the conditions of the motors are reversed. The stall torque will add to the power losses of the gear train, and the efficiency of this system is also low (dependent on the stall torque setting).

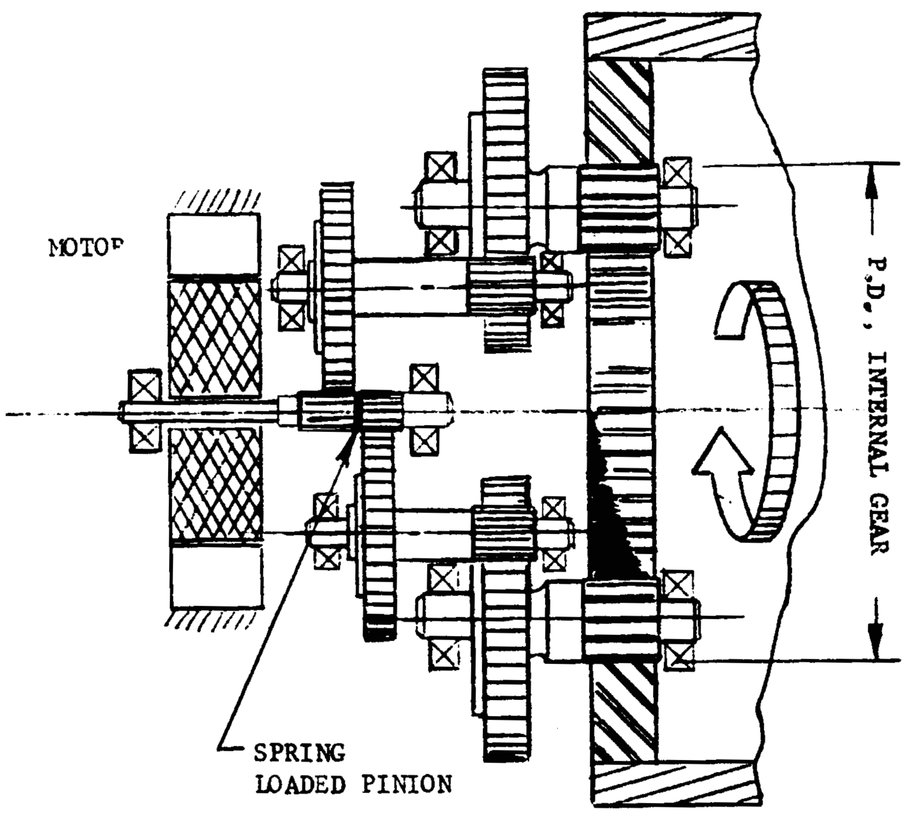


Figure V-19 Dual Gear Train with Spring Loaded Pinion

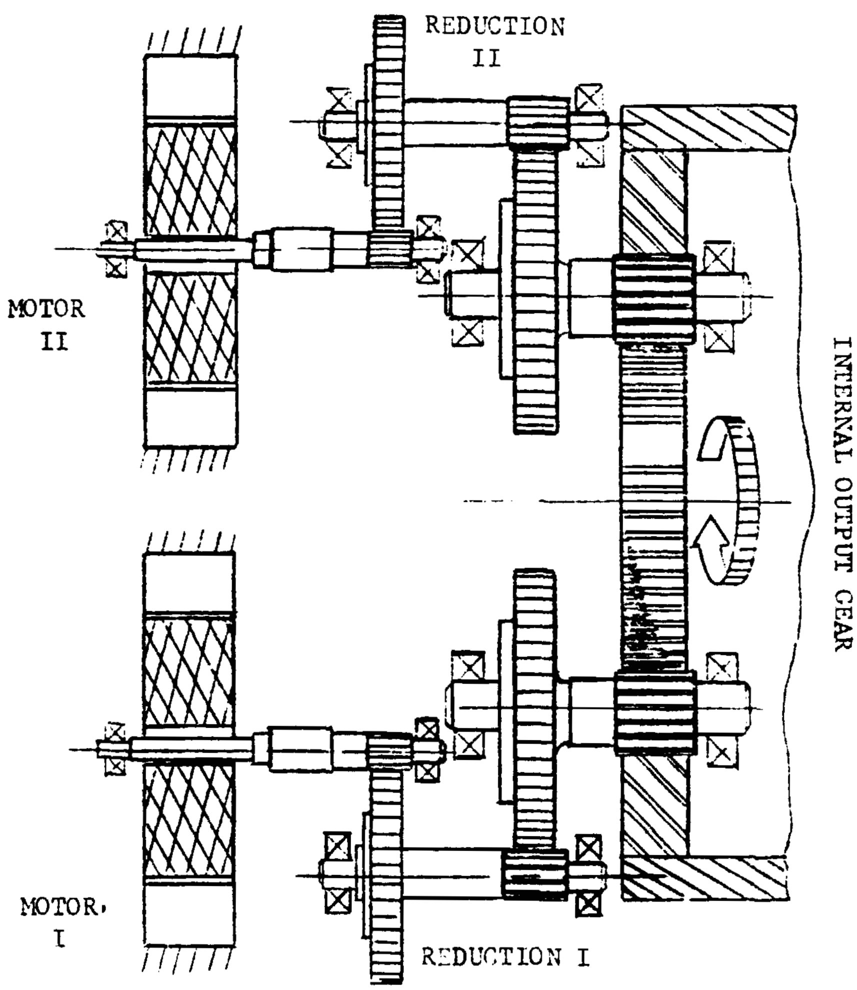


Figure V-20 Dual Gear Train with Two Independent Motor Drives

(3) External Gear System - Due to the fact that the manufacture of external gears is somewhat less expensive than the internal one, an external gear system, shown in Fig. V-21, was also considered. An external gear could be used in both of the two systems mentioned above. The disadvantages lie mainly with its awkwardness as a joint and the torsional problems for the solid thin shaft. The gear housing will be larger; thereby the joint will weigh more than the equivalent system with an internal ring gear. The efficiency is estimated to be about the same as (1) and (2) previously discussed.

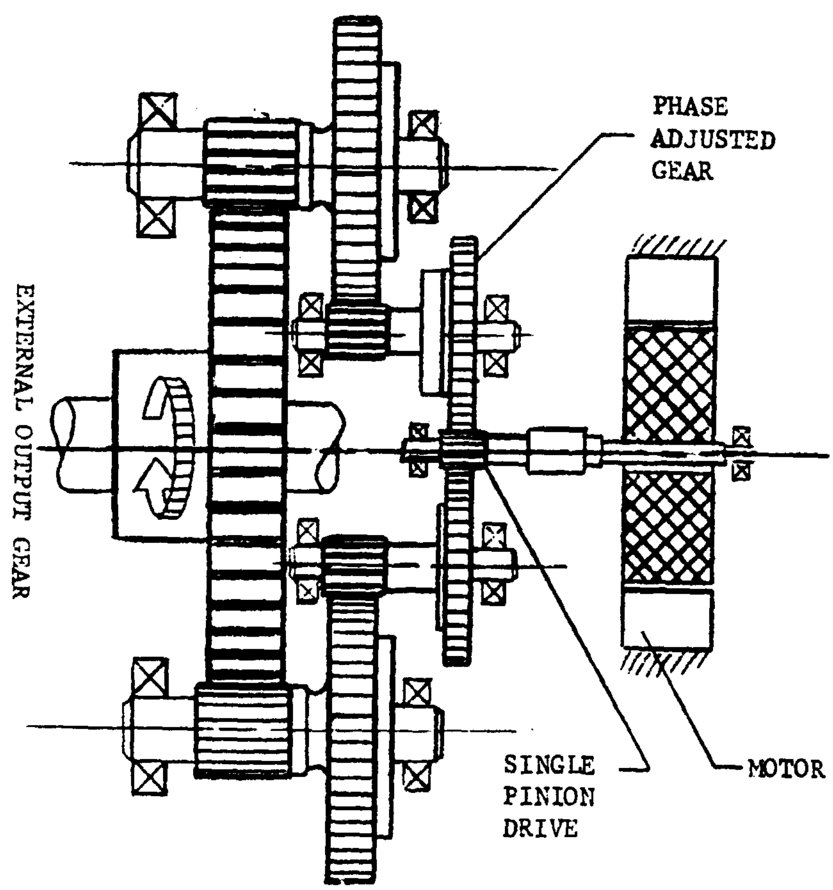


Figure V-21 External Ring Gear System (Phase Adjusted)

(4) Differential Planetary Drive - This planetary gear speed reducer provides a large gear ratio. The number of components is considerably less than the first three systems. This system, shown in Fig. V-22, utilizes two internal (external) ring gears of the same pitch diameters. One of the two ring gears has one tooth less for maximum ratio, and consequently its diameteral pitch will be a fraction lower. These gears can be manufactured the same way as the full standard diameteral pitch gears. Every revolution of the motor shaft which carries the planet gears therefore makes the ring gears move relative to each other by an angular motion of the size of one tooth. The respective planet gears have an identical number of teeth, and their diameteral pitches match those of the ring gears. For a higher capacity of the system, a number of planet gears may be used. Under standard efficiency range condition this gear train cannot be used as a speed increaser. That is, the mechanism will prevent power flow from the manipulator to the brake. Its merit lies in its single mesh high reduction capability, load carrying capacity, compactness and its lightweight design.

(5) Harmonic Drive - A fixed internal output ring gear meshes with the external teeth of a thin flexible inner ring of smaller pitch diameter than the rigid gear as shown in Fig. V-23. Inside these two gears, a wave generator rotates and meshes the two gears at two or more places. The drive permits high speed ratios and high torque capacities. It backdrives (speed increaser) with low efficiency and has a high torsional windup. Due to its strong teeth-to-teeth meshing characteristics, the harmonic drive is a doubtful performer under the extreme environmental conditions of space.

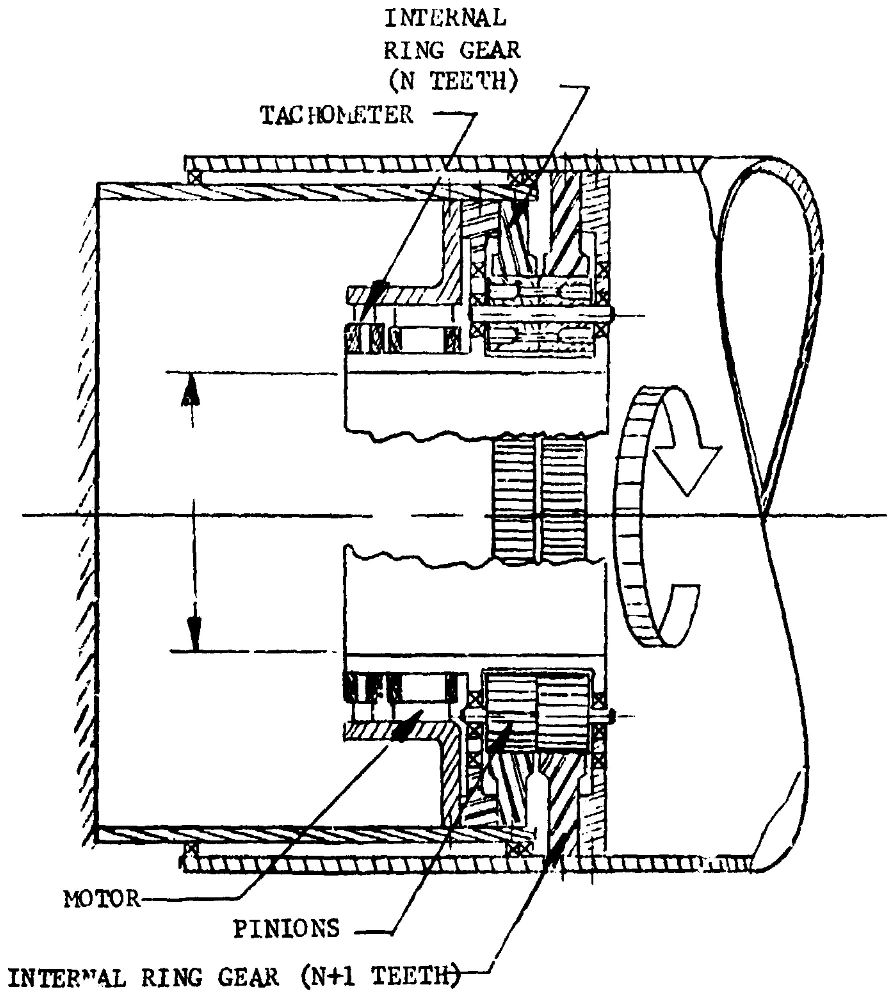


Figure V-22 Differential Planetary Drive

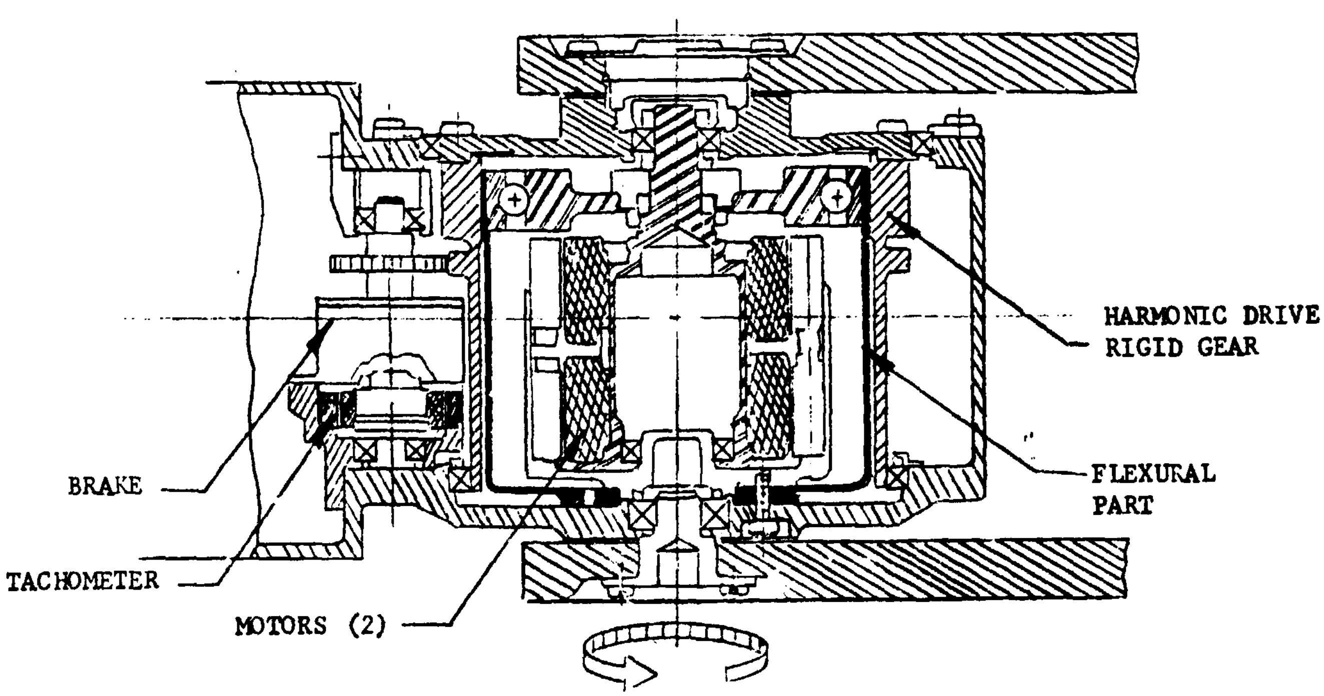


Figure V-23 Harmonic Drive

(6) Planocentric Train - A fixed internal ring gear meshing with an eccentrically mounted external-tooth-gear, which is only slightly smaller, is illustrated in Fig. V-24. The input is to the eccentric shaft, and the output is taken from the pinion through a pin coupling which permits radial displacement. A single mesh high reduction ratio can be obtained. However, this system cannot be used as a speed increaser.

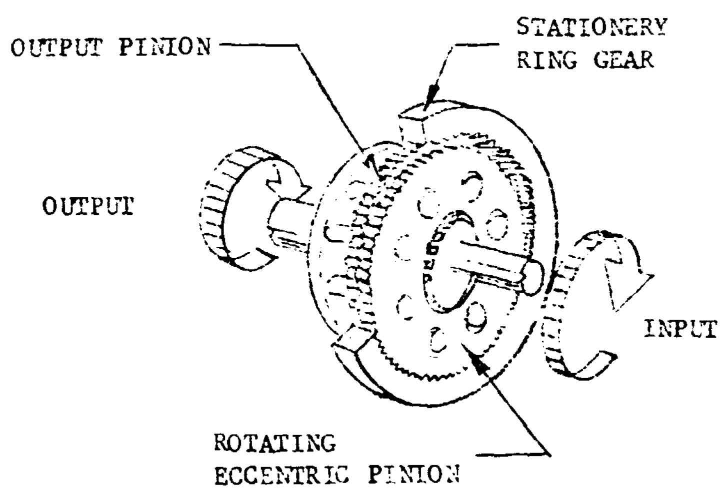


Figure V-24 Planocentric Gear Pair

(7) Nutation Drive - A nutating member carries cam rollers on its periphery and causes a differential rotation between the three major components of the drive: stator, nutator, and rotor. This drive, shown in Fig. V-25, has high speed reducer efficiency, but it is unable to perform as a high efficiency speed increaser. It is new on the market, and the price of development of various sizes for the manipulator application could be prohibitively high. Furthermore, this drive is also a marginal performance as a speed increaser.

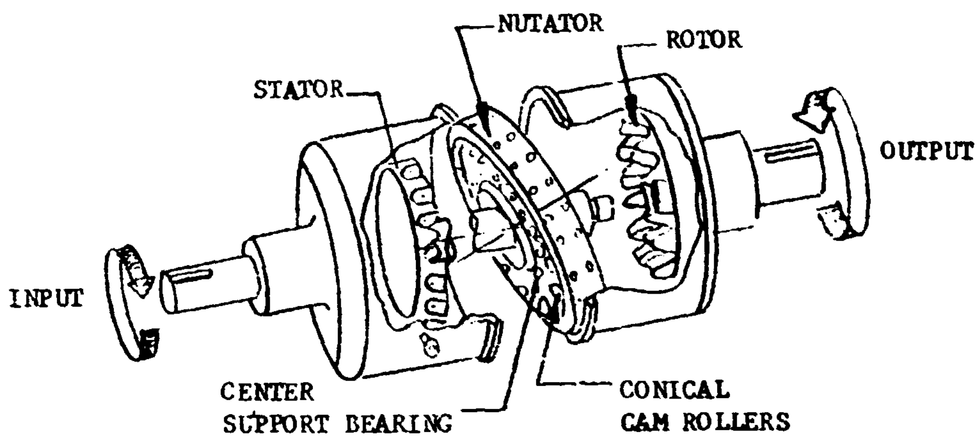


Figure V-25 Exploded View of the Nutation Drive

(8) Dual Gear Train, Out of Phase System - This could be called a compromise design, which allows some predetermined backlash sufficiently enough to avoid cogging under environmental conditions and allows the system to operate at high efficiency either as speed increaser or speed reducer.

Although this drive uses several gears and components, as shown in Fig. V-26, it is important to point out here that this drive will fulfill all the critical requirements necessary to build a reliable manipulator arm joint.

This gear train is rather sensitive to assembly procedures, as far as care and caution is concerned. The mounting of one gear of one of the two paths must be customized for each joint. The desired backlash at the output pinion should be shimmed and then the out of phase mounting of gears can be accomplished. At no backlash this gear train will not operate efficiently. Cogging and tightening occur. Therefore, a built in backlash is mandatory for this system.

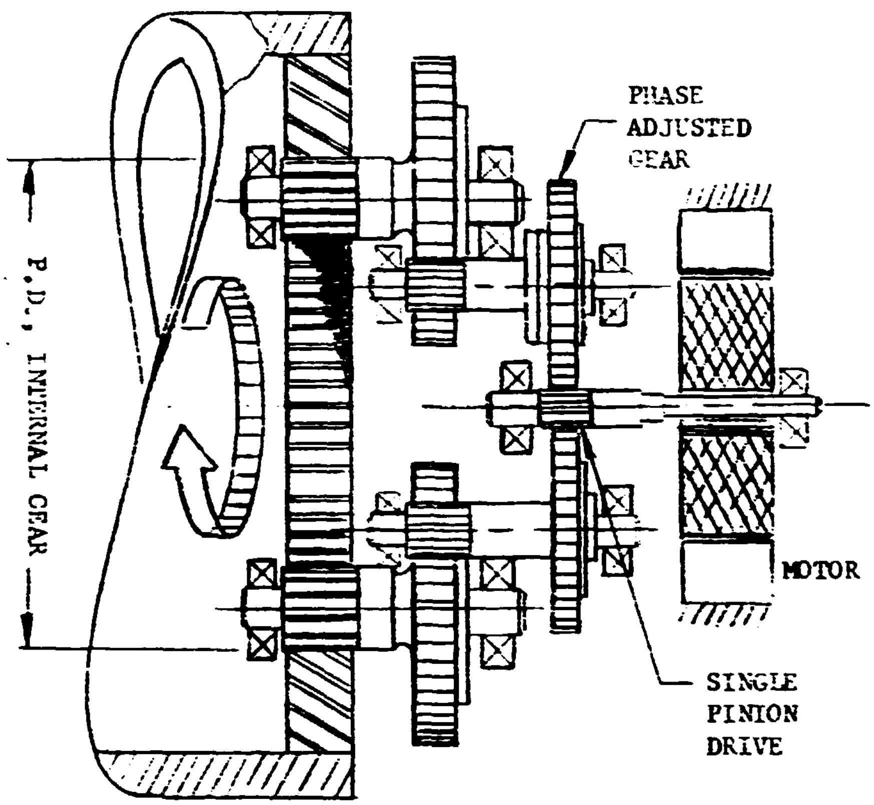


Figure V-26 Dual Gear Train Out of Phase Internal Output Gear System

Based upon the preceding discussion, the dual branch gear train, out of phase system was initially selected. (Note: As discussed in Section VII, Preliminary Design, this was later modified to four branches).

Additionally, based upon previous related work contained in Ref. 7, the desirable gear ratios lie in the range of from 25:1 to 50:1.

3. Lubrication Considerations

Before one can continue with the design of the gear train, the problems that various lubricants encounter under severe environmental conditions must be considered. Providing effective lubrication for mechanisms used in a space environment is the major factor affecting the design of the mechanism. The ambient conditions are:

Temperature: $-100°F$ to $+200°F$
Pressure: 10^{-10} Torr

These ambient conditions rule out any known wet lubricants, petroleum base oils, or manmade lubricants of other chemical formulation, primarily because of the wide temperature range and the long storage and work life requirement expected for the FFTS manipulator arm. Dry film lubricants can perform satisfactorily in the space environment but have a limited life capability (i.e. M_0S_2, etc.).

Since it is recognized that the wet film lubricants provide superior lubrication, less friction and wear, and longer life than other lubricants, one possible way to use these wet lubricants is to maintain the chamber at a minimum of -100°F temperature, provide a sealed (pressurized) environment for the mechanisms, and have a lubricant reservoir next to the gears and bearing. A ring shaped of porous phenolic or nylasint material, vacuum impregnated with oil and placed adjacent to the areas requiring lubrication, may be a satisfactory solution for long-life lubrication. SKF has a reservoir scheme named "poly oil" that uses ribbon type metal ball retainers enshrouded by a plastic sponge material. For gears, F-50 lubricant would be the recommended choice. These and some other candidate lubricants are summarized in Table V-7.

All the above lubrication schemes will either be used as short life lubricants (like dry films) or the wet lubricants which are the long life variety that would require not only elaborate design but extra power to maintain pour point temperatures because of their high kinematic viscosities. At the pour point temperature, these lubricants can cause extremely high stiction on gears and bearings.

The above reasoning has led to the decision to eliminate dry or wet lubricants from consideration in this manipulator arm design.

Table V-7 Candidate Liquid Lubricants

DESIGNATION	MANUFACTURER	CHEMICAL DESCRIPTION	VOLATILITY, % LOST UNDER CONDITIONS SHOWN	VAPOR PRESSURE, MM HG	VISCOSITY, CENTISTOKES P.P. △ POUR POINT
VERSILUBE F-50*	General Electric Company	Fluid - Chlorophenyl - Methyl Polysiloxane	1.4% @ 302°F, 1 atm, 24 hr. 1% @ 150°F, 10^{-5} Torr, 24 hr.	1 @ 125°F	P.P. -100°F 2500 Ck @ -65°F 4.5 Ck @ 400F
AEROSHELL 17** 22**	Shell Oil Company	Fluid - Diester (MIL-G-21164C) Fluid - Synthetic Hydrocarbon (MIL-G-81322A)	.8% @ 210°F, 1 atm, 22 hr. 4.2% @ 350°F, 1 atm 22 hr.		PP-100 3.1 @ 210 PP-85, 7.7 @ 210
KRYTOX 143 AZ	duPont Corporation	Perfluoralkyl Polyether	19% @ 300°F, atm, 6.5 hr.	2.2 @ 300°F	PP-70F 8000 @ -40° .8 @ 400°F
NPT4	Bray Oil Company	Synthetic Esther Base Oil	6.5% @ 400°F, 1 atm, 6.5 hr.		PP Below -80°F 26900 @ -65°F 4.4 @ 210

NOTES: * In grease form designated G-300.
** Marketed as a grease.

The imposed environmental condition and design requirements therefore dictate the use and consideration of solid lubricants. They provide the most promise in this application. After a thorough evaluation of several commercially available solid lubricants, the "Hl-T" lubricant by General Magnaplate was selected as a candidate*. The Hl-T lubricant has the following features which other lubricants do not possess:

- Insensitivity to high loading at extreme temperatures
- Rapid dissipation of surface temperatures from pressure contact areas

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* Information was obtained via telephone conversations with Dr. Charles P. Covino, President of General Magnaplate Corp.

- Good adherence to base metal irrespective of temperature and environmental changes
- Long life under extreme operating conditions of sliding and rolling friction
- Compatibility with most chemicals, oil, gases and metals
- Self healing into an integral part of the bearing surface by heat and pressure

However, the two most important properties of H1-T lubricant which encouraged its selection are: (1) Can be operated at or up to 140,000 psi contact stresses for long life cycle, and (2) normally functions within the -200°F to +200°F temperature range.

Good surface finish and surface hardness on the bearings and gears on which the H1-T lubricant is to be deposited will improve the lubricants, and consequently the manipulator arms' life considerably (Ref. 16 and 17).

4. Additional Actuator Components

a. Brakes - Due to the design of the motor/gear train assembly, which is easily backdriven, a fail-safe brake is required in each motor/gear train assembly. The primary function of this brake is to hold the manipulator in any given configuration with little or no power consumption. The brake may also be used to hold a single DOF in position upon command by the operator or by incorporation of brake control logic in the control laws such that the brake is automatically applied.

Electric brakes are available in four basic types: magnetic-particle, requiring power applied to engage; eddy-current, which cannot be operated at zero torque; hysteresis, requiring power applied to engage; and friction which is capable of performing a fail-safe function by being engaged with no power applied, and is completely disengaged when energized.

The most widely used electric brake is the electromagnetic friction-disc type, in which a friction unit can be electrically engaged or disengaged. These are normally used for on-off operation. For variable torque retarding, as in tensioning applications, pure-electrical brakes (magnetic particle, hysteresis, or eddy-current) are normally used. The electromagnetic friction-disc type brake is recommended for use on the manipulator due to its fail-safe characteristics as well as its simplicity of operation and on-off operation.

The electromagnetic friction brakes are normally used to provide near maximum torque in milliseconds from high speed. They have no residual drag when disengaged and develop maximum torque at zero speed. Although friction-disc brakes are subject to lining wear, when they are properly applied within their thermal capacity and stopping time, 2.5 million or more stops can be attained on a set of linings.

Disc brakes are available in three basic types. In one type the brake is engaged electrically. Stopping is accomplished by energizing a stationary, friction-faced, magnetic coil that attracts a rotating armature disc. In the other type, the brake is spring-engaged and magnetically released. Friction discs within the brake revolve with the brake hub, which is rigidly mounted to the motor shaft. When the magnet coil is deenergized, the spring loaded pressure plate presses against the rotating friction discs. This type of brake is inherently fail-safe; if power fails, the brake will set automatically until power is restored. A third type of disc brake which is not readily available but which could be implemented on the manipulator utilizes a ratchet system to engage and disengage the brake. This brake requires external electronics to produce a fail-safe feature due to its ratchet action which requires a pulse to change its state from either engaged to disengaged or disengaged to engaged. The major advantage of this type of brake is to minimize power consumption at the cost of a less fail-safe system.

Two of three friction disc brakes mentioned above meet the basic fail-safe requirements: the spring engaged brake and the ratchetting brake. The most fail-safe of these two is the spring engaged, however, this unit requires continuous power application to disengage the brake. This disadvantage has been demonstrated in MMA labs to be small by taking advantage of an inherent feature of this brake. Namely, that once the brake is disengaged the power to hold the brake disengaged may be reduced. Tests performed by MMA on typical brakes of this type which meet the requirements for manipulator application have shown that the power required to hold the brake disengaged is 1/10th the factory rated power consumption. Typically the amount of power necessary to actuate the brake is 0.25 watt-sec at 24 volts. The power needed to hold actuation is 0.7 watts for the largest brake and 0.4 watts for the smaller brakes. The magnitude of this brake will be sized to the required maximum tip force which the motor exerts.

b. Position Sensors - The function of the position sensor on each DOF of the manipulator is to produce an electrical signal proportional to the angular position of each DOF. This signal may be used simply to indicate to the operator, via visual readouts, the different joint angles, or may be used in control laws for closed loop position control, or derived rate control by differentiating this signal. The three different possible uses require different position sensor requirements. However, in general the closed loop position and derived rate control have comparable resolution and linearity requirements.

Potentiometers will be used for this application. Of the types that are available, the resistance potentiometer is the most versatile and widely used. They will either be directly connected to the output shaft or will use antibacklash gears for precise positioning capabilities.

c. Rate Sensors - The variety of speed-measuring devices is endless, and possibly in specialized control applications very unusual techniques may be found. However, this coverage will be limited to those techniques that have found more or less common usage in control systems. This limitation is established by accuracy requirements and ease with which the output signal can be converted to a usable form.

The types of speed-measuring devices most commonly used in control systems are given below:

- Tachometers - These devices obtain reasonably good accuracy, but suffer somewhat from reliability.

  Advantages: Freedom from waveform and phase-shift problems, absence of residual output at zero speed, very high gradients in small size (0.2 to 85 volts/rad/sec), and can be used with high-pass output filters to reduce servo velocity lags.

  Disadvantages - Brush problems, generation of radio noise, output ripple, and slightly higher torque requirements due to brush friction and hysteresis effects.

- Operation Circuits - The output of these devices is the analog computed rate, derived from position data, and is only a close approximation to a linear relationship. They are useful primarily in rough computation problems, and for derivative stabilization.

  Advantages: Reduction in system size and weight and no extra electro-mechanical sensors other than a potentiometer.

  Disadvantages: External electronics required and accuracy restricted to differentiation circuits.

- Bridge Circuits - DC bridge circuits measure the motor counter emf which is directly proportional to speed for constant field excitation and temperature. This approach is practical and widely used. However, there is poor accuracy at low speeds and near stall torques.

<u>Advantages</u>: Simplicity, reduction in system size and weight, and no extra electro-mechanical sensors other than a potentiometer.

<u>Disadvantages</u>: External electronics required, temperature sensitive, and poor accuracy at lower speeds.

As the rate sensor is to be used in the control system, the preliminary selection is given to the use of tachometers.

VI. MAN-IN-THE-LOOP SIMULATIONS

Man-in-the-loop simulations were conducted. The purpose of the simulations was four-fold: (1) evaluate the comparative merits of unilateral rate and bilateral position control, (2) determine the functional capabilities of the newly fabricated manipulator arm, (3) examine the operational capabilities of the newly constructed nongeometric bilateral controller, and (4) investigate the usefulness and workability of the data displays and operator controllable functions incorporated in the operator's control console.

A complete description of the simulation program and the hardware implemented is contained in Appendix E. Briefly, from the information gained during the simulation, the range/azimuth/elevation/rotation rate control technique was found to be the most versatile and simplest method for manipulator control. Therefore, this technique was baselined for the preliminary design phase of this study.

VII. PRELIMINARY DESIGN

The preliminary design was based upon both the detailed requirements analysis and trade studies, contained in Section V, and the results and recommendations of the man-in-the-loop simulations, summarized in Section VI and detailed in Appendix E.

A. MANIPULATOR SYSTEM

The preliminary design drawings for the FFTS manipulator system are shown in Figs. VII-1 through VII-7. The following paragraphs discuss the detailed aspects leading to this preliminary design.

1. Gear Design

As indicated in Section V, the design of the gears (and bearings) are highly influenced by the selected lubrication scheme. Using the solid lubricant, it was found that to provide stress levels within the allowable range a four branch system, rather than the dual, was required. Furthermore, the previously predicted gear train ratios were reduced to a range of 25:1 to 50:1 as the pinion diameters must be increased.

a. Gear Train - The normal iteration method of gear train design becomes more complex when the consideration of low contact stresses are added. The equation for contact stresses was investigated and the sensitive properties were noted. In order to get low load per gear mesh, the load carrying pinions were doubled up by the introduction of two more gear branches into the candidate "out of phase" type of design. Additionally, the face width of the gear and the pinion diameter product were maximized by the increase of gear face width to the maximum permissible level allowed for good quality gears. The pinion size was also increased to its maximum level. As a rule of thumb the 12 teeth pinions were selected as a minimum, using the lowest diametral pitch gears whenever possible.

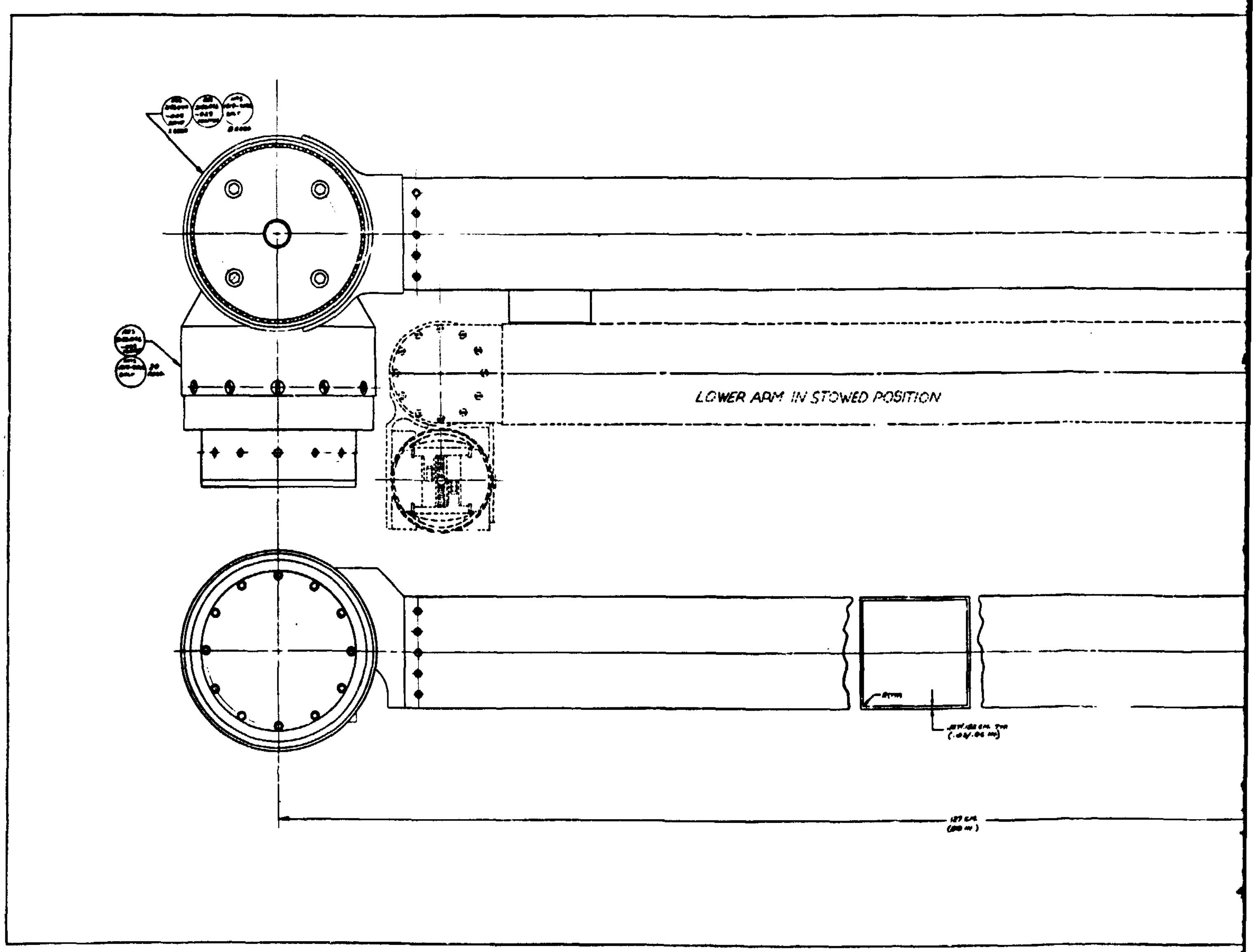
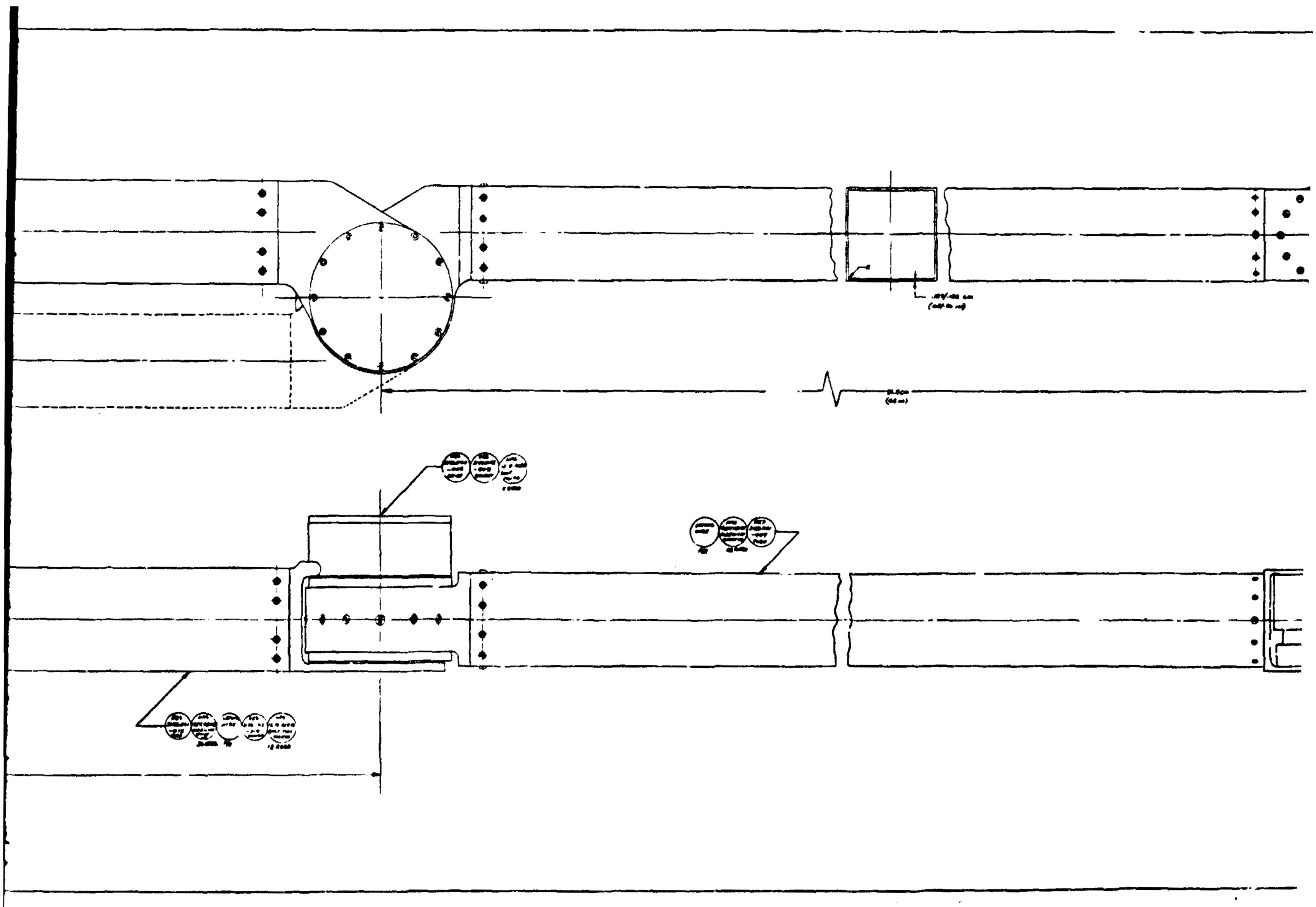


Figure VII-1 Final Assembly Drawing of FFTS Manipulator Arm

FOLDOUT FRAME



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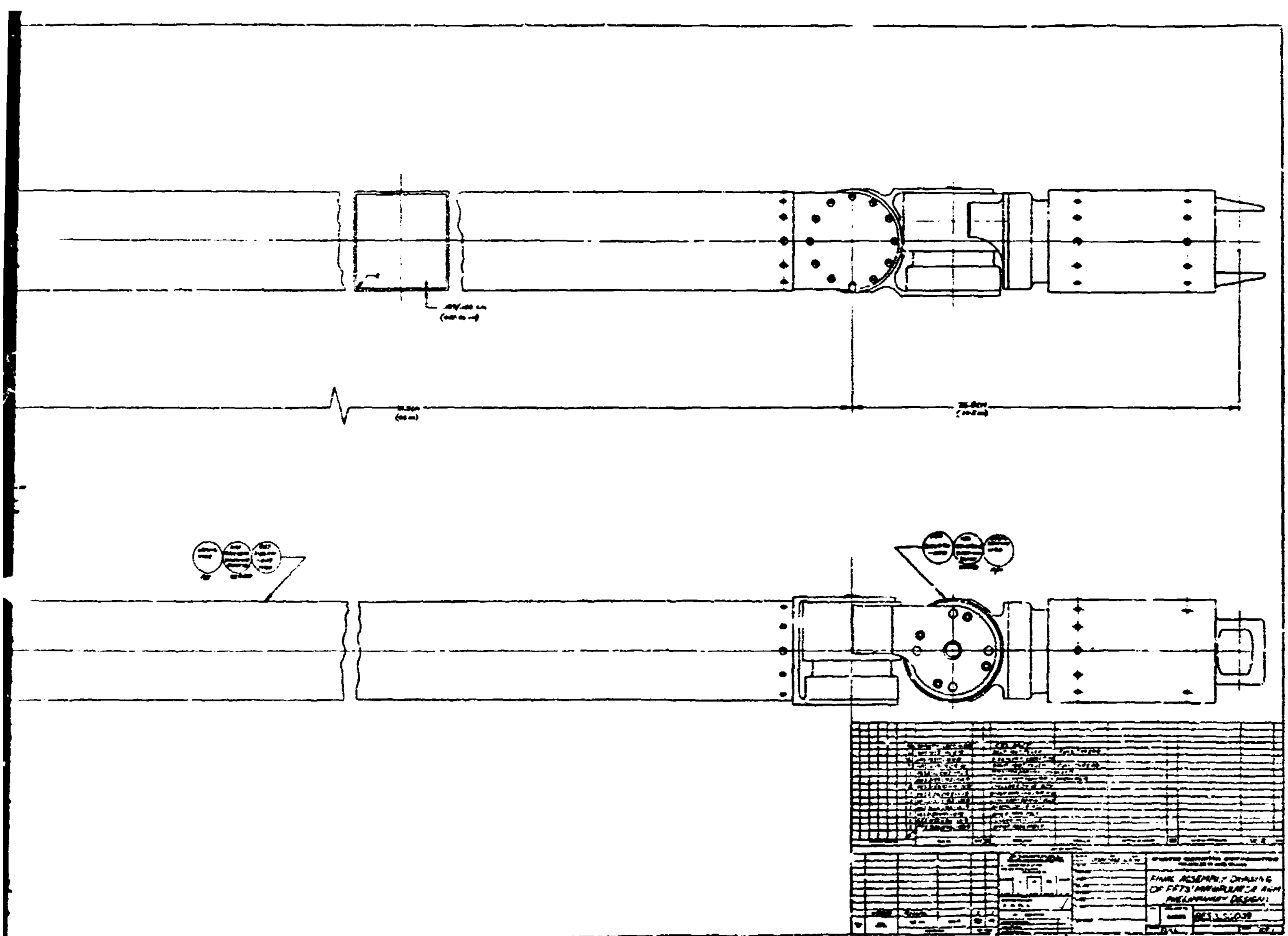

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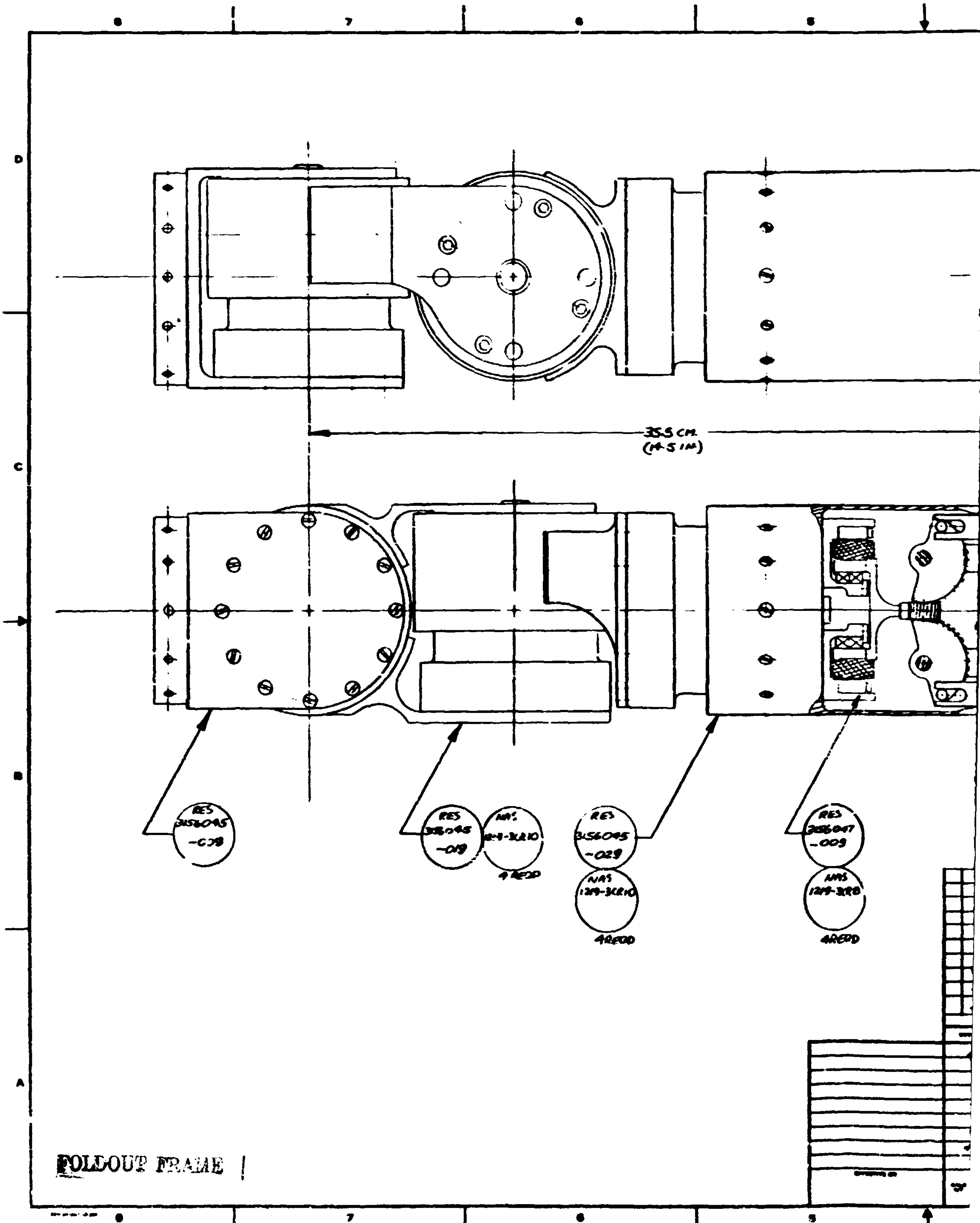
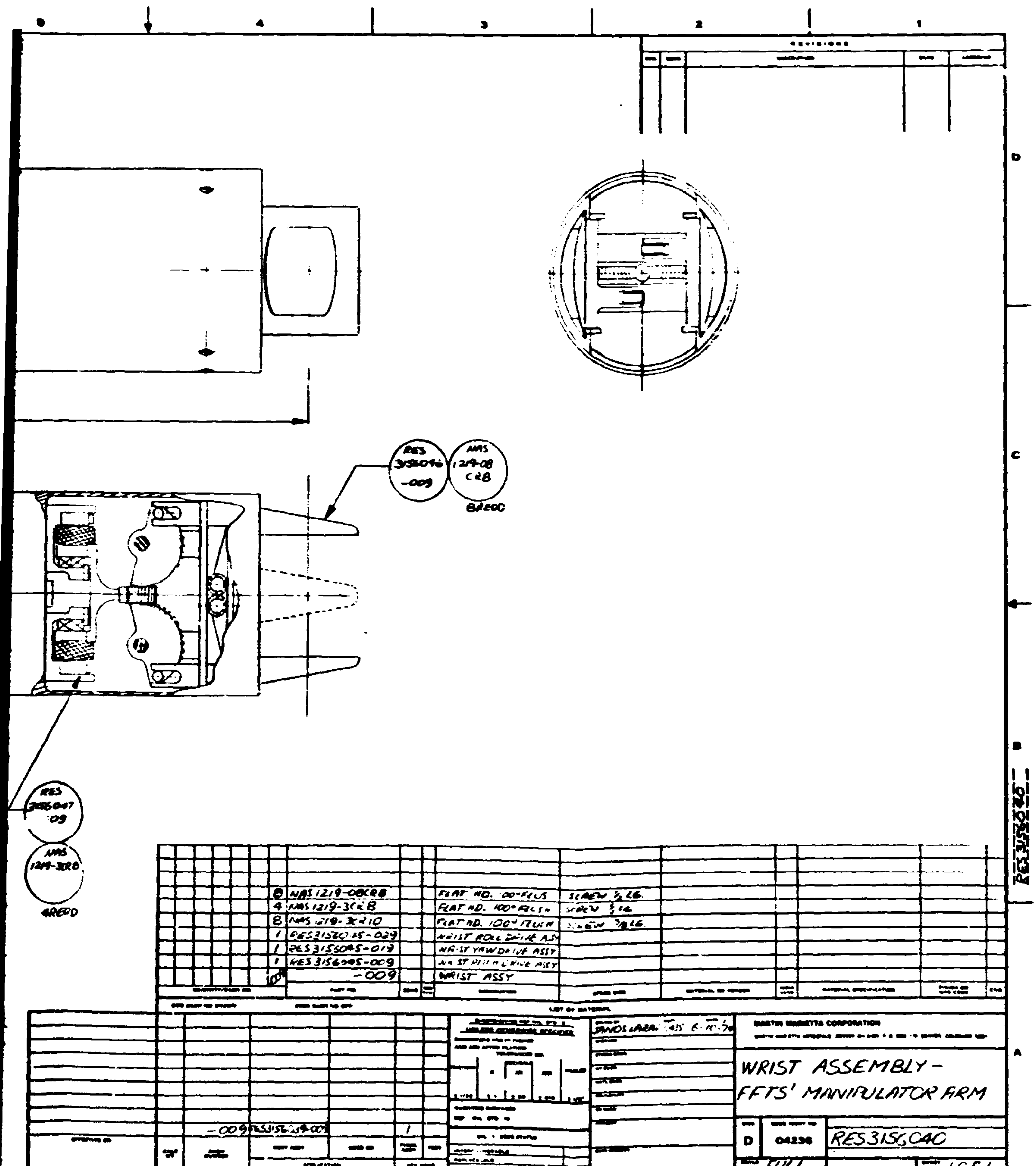


Figure VII-2   Wrist Assembly



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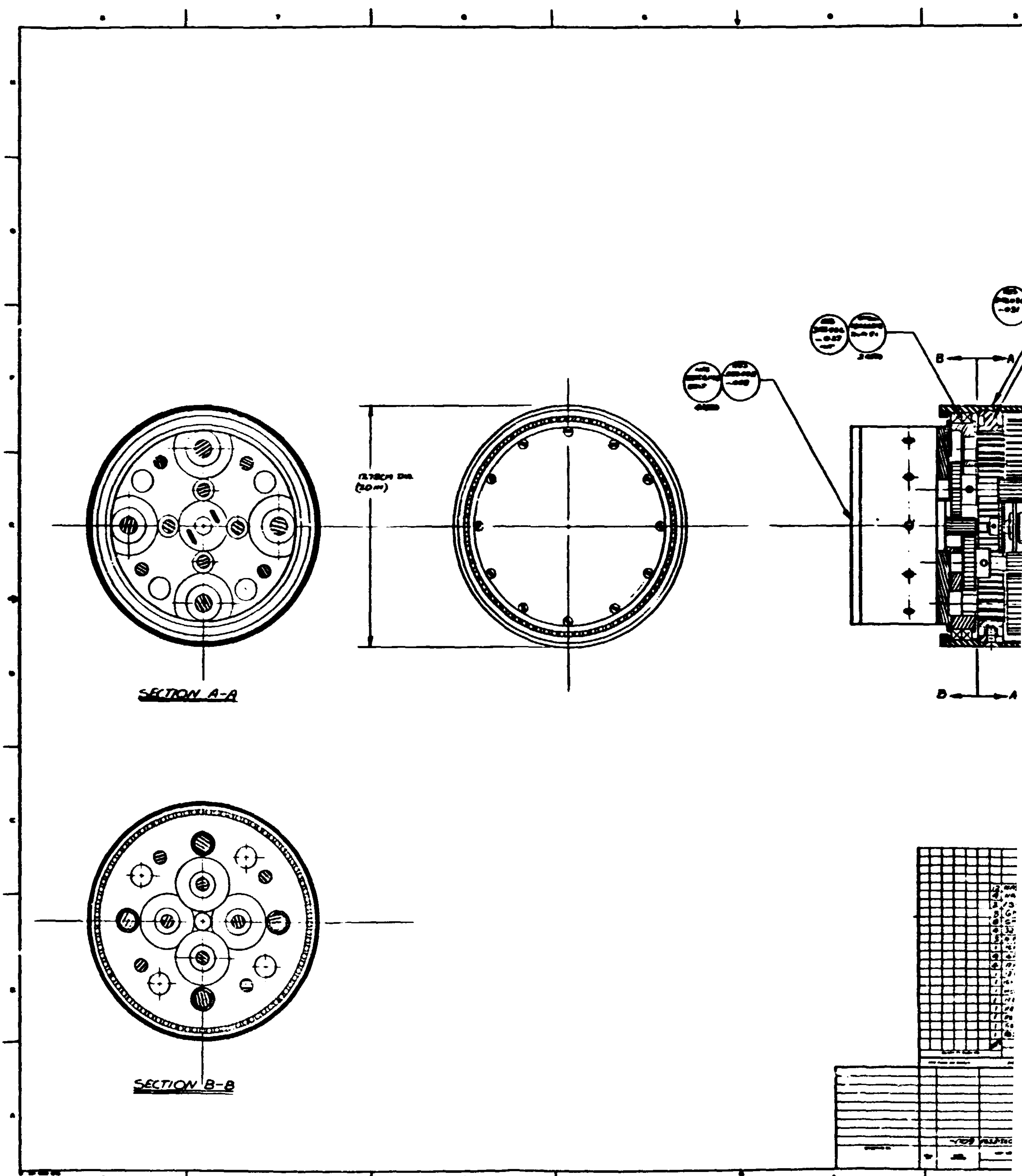
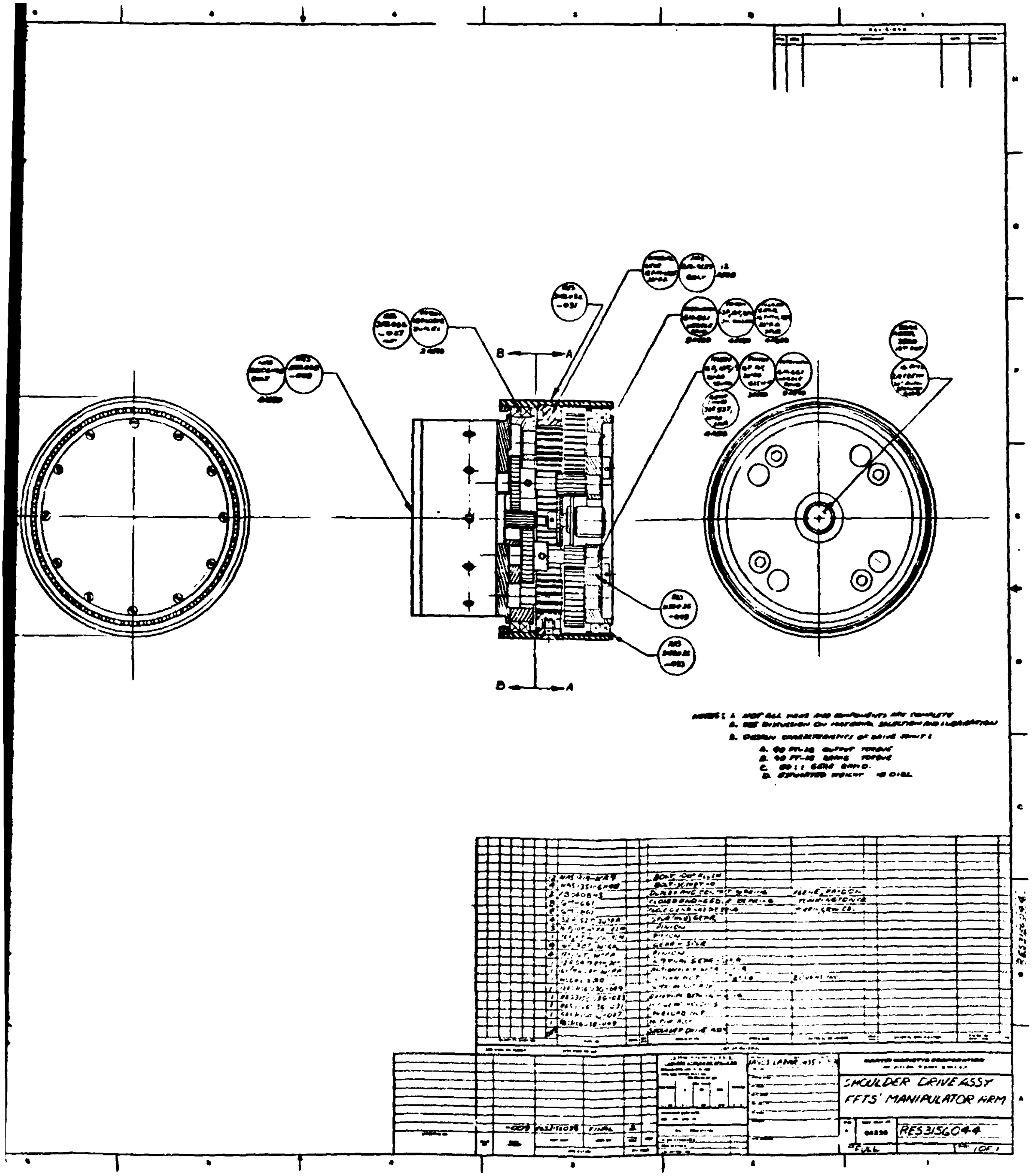


Figure VII-3 Shoulder Drive Assembly

FOLDOUT FR



VII-7 and VII-8

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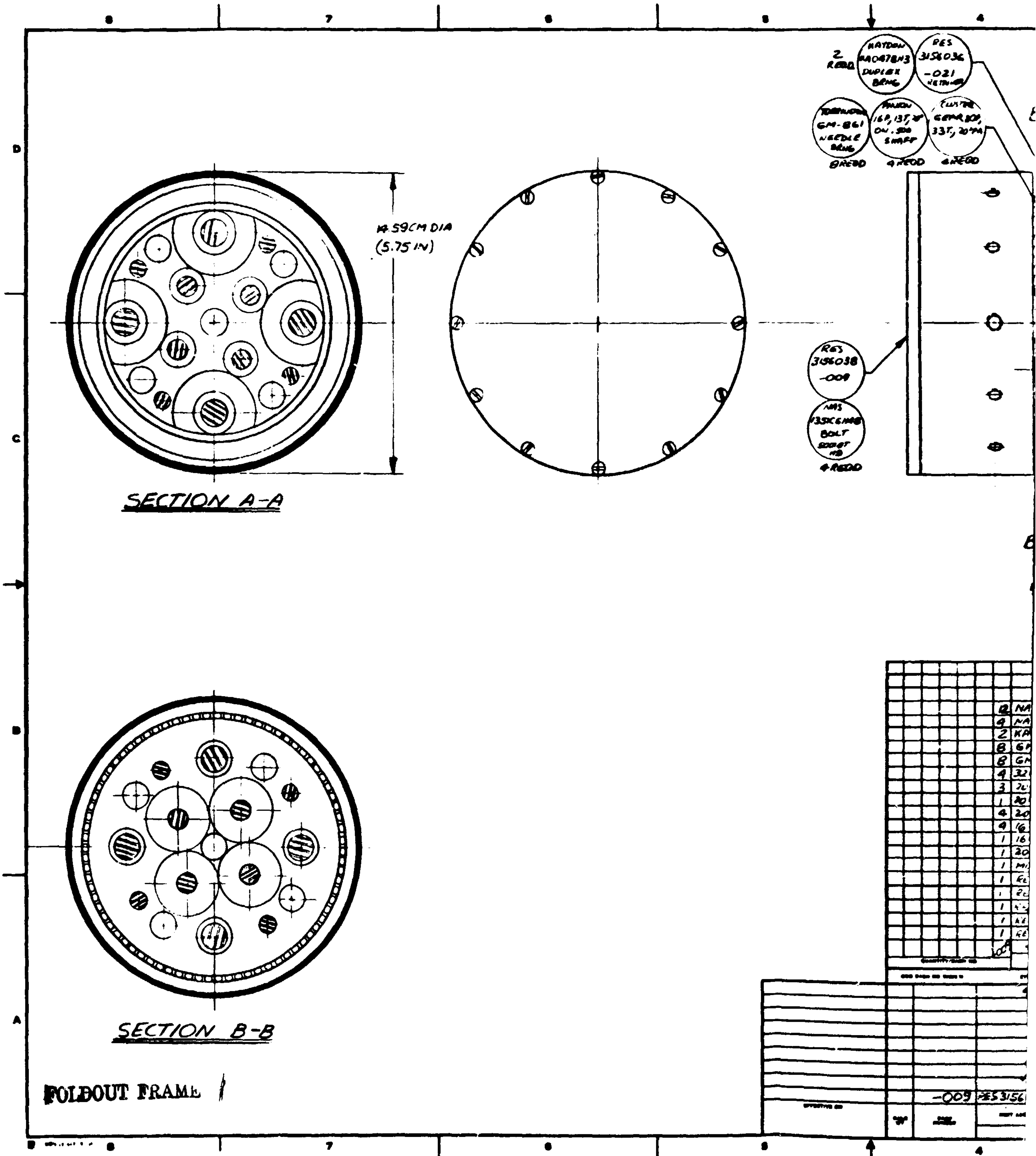
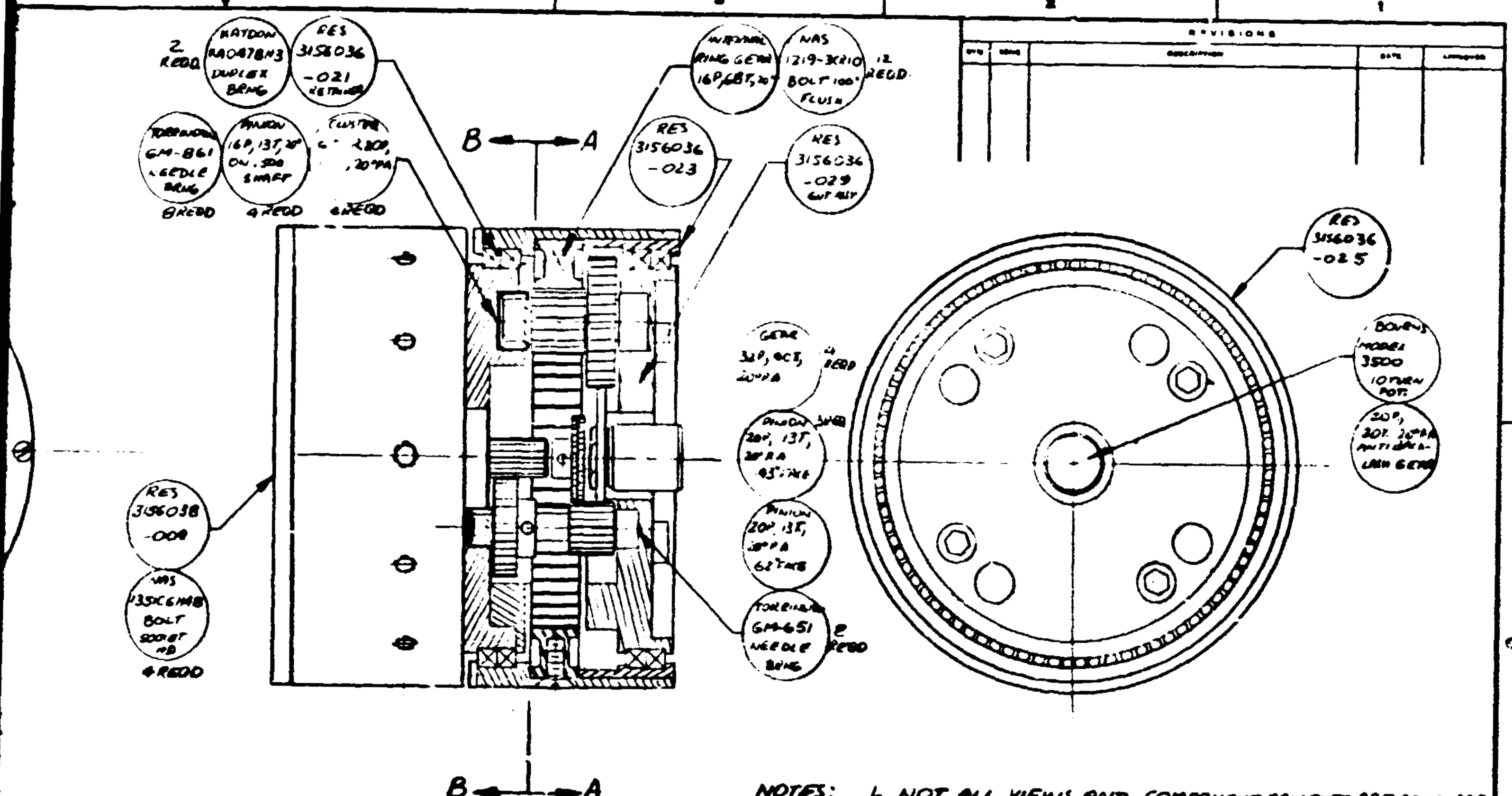


Figure VII-4 Elbow Drive Assembly



NOTES:
1. NOT ALL VIEWS AND COMPONENT CALLOUTS ARE COMPLETE.
2. SEE DISCUSSION FOR MATERIAL SELECTION & LUBRICATION
3. DESIGN CHARACTERISTICS OF DRIVE JOINT:
   A. 50 FT-LB OUTPUT TORQUE
   B. 50FT-LB BRAKING TORQUE
   C. 332:1 GEAR RATIO
   D. ESTIMATED WEIGHT 14 LBS.

QTY	PART NO.	DESCRIPTION	STOCK SIZE	MATERIAL OR VENDOR
12	NAS1219-3CR10	BOLT 100° FLUSH		
4	NAS1351C6H48	BOLT SOCKET HD.		
2	KA047BN3	DUPLEX BALL BEARING		KEENE (CAA-KAYDON
8	GM-B61	NEEDLE BEARING		TORRINGTON CO.
8	GM-651	NEEDLE BEARING		TORRINGTON CO.
4	32PITCH, 40T, 20°PA.	GEAR-HUB		
3	20PITCH, 13T, 20°PA.	PINION	.43 FACE	
1	20PITCH, 13T, 20°PA	PINION	.62" FACE	
4	20PITCH, 33T, 20°PA.	GEAR		
4	16PITCH, 13T, 20°PA.	PINION ON .500 SHAFT		
1	16PITCH, 52T, 20°PA.	INTERNAL RING GEAR	5/8" FACE	
1	20PITCH, 20TEETH	ANTI-BACKLASH GEAR		
1	MODEL 3500	10 TURN POTENTIOMETER (WIRE WOUND)		
1	RES3156036-029	INTERNAL 'GUT' ASSY.		
1	RES3156036-025	INTERNAL GEAR HOUSING		
1	RES3156036-023	EXTERNAL BEARING HOUSING		
1	RES3156036-021	RETAINER		
1	RES3156038-009	MOTOR ASSY.		
	-009	ELBOW DRIVE ASSY		

LIST OF MATERIAL

-009 RES3156039-009 1

APPLICATION

DRAWN BY JANOS LAZAR 5435 6-8-74

MARTIN MARIETTA CORPORATION

ELBOW DRIVE ASSEMBLY
FFTS' MANIPULATOR ARM

D 04236 RES3156042

SCALE FULL SHEET 1 OF 1

RES3156042

FOLDOUT FRAME 2

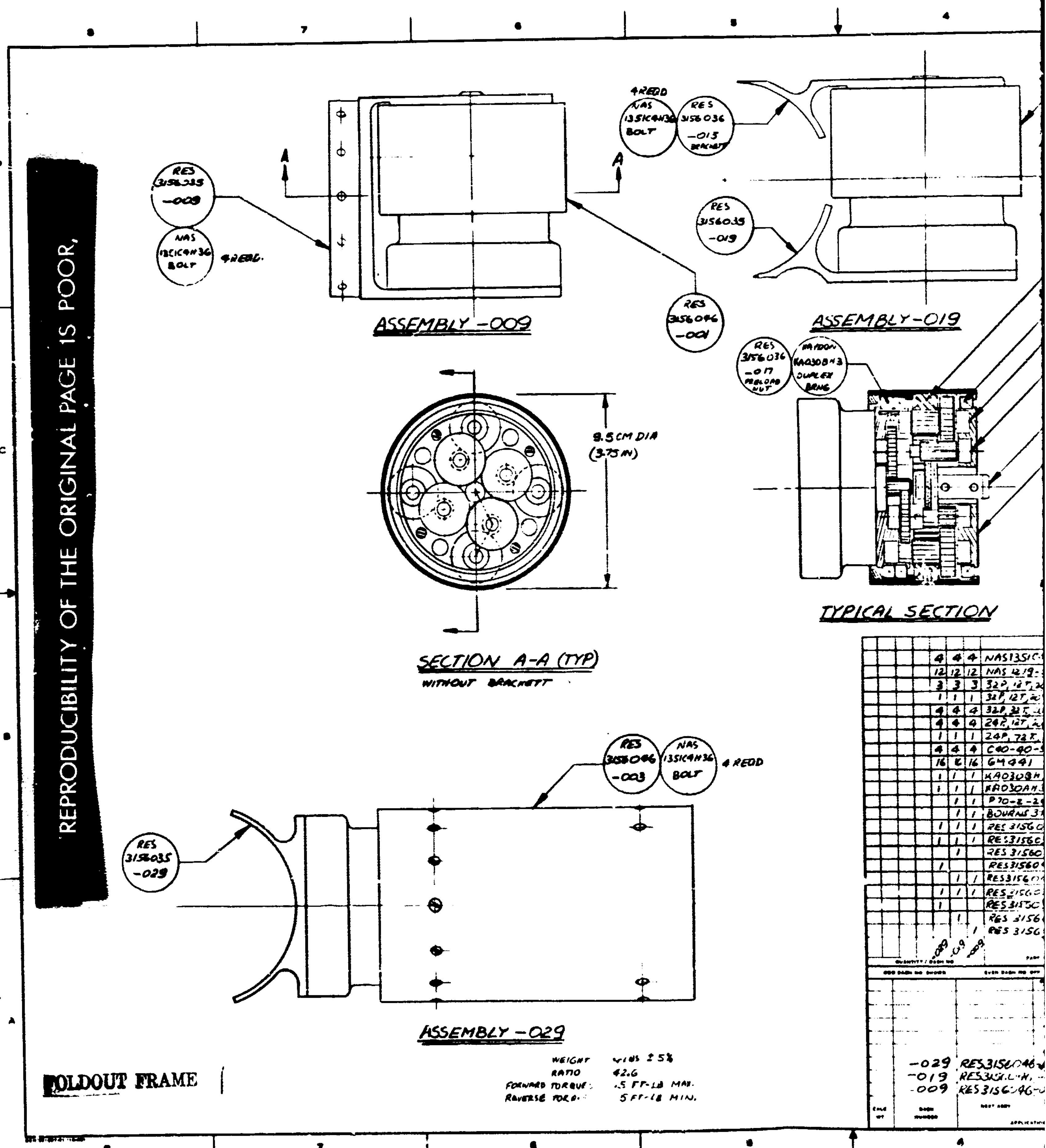


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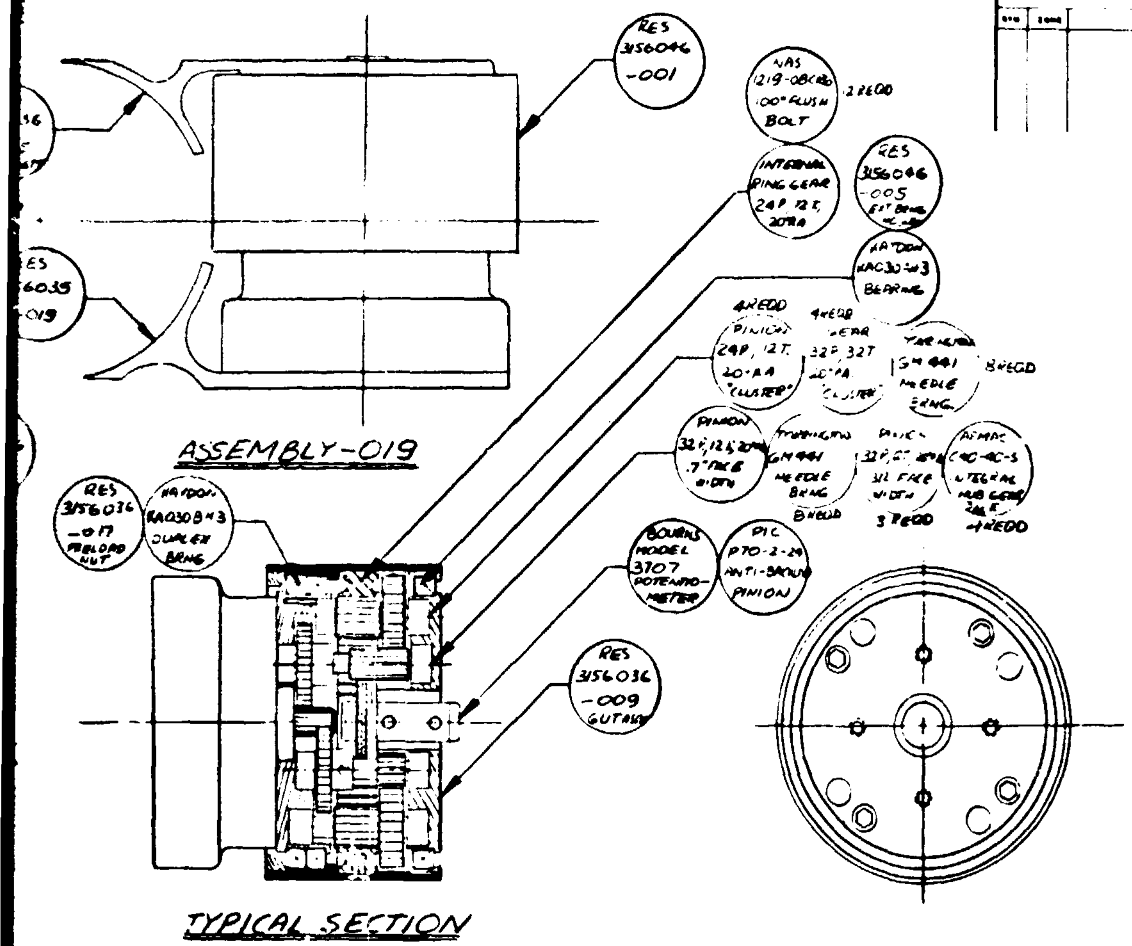
Figure VII-5 Wrist Drive Assembly



NOTES: 1. SOME VIEWS AND CALLOUTS ARE INCOMPLETE.
2. SEE DISCUSSION FOR MATERIAL SELECTION & LUBRICATION
3 FOR -029 (WRIST ROTATION) A CONTINUOUS SINGLE TURN POTENTIOMETER WILL BE USED

4 REQD

-029	-019	-009	PART NO	DESCRIPTION	STOCK SIZE	MATERIAL OR VENDOR	NOTE
4	4	4	NAS1351C4H36	BOLT, SOCKET HEAD			
12	12	12	NAS 1219-08CRG	BOLT 100° FLUSH			
3	3	3	32P, 12T, 20°PA	PINION	.31 FACE		
1	1	1	32P, 12T, 20°PA	PINION	.75 FACE		
4	4	4	32P, 32T, 20°PA	GEAR "CLUSTERED"	¼ FACE		
4	4	4	24P, 12T, 20°PA.	PINION ON ¼ SHAFT	.56 FACE		
1	1	1	24P, 72T, 20°PA	INTERNAL RING GEAR	½ FACE		
4	4	4	C40-40-S, 1/16 FACE	INTEGRAL HUB GEAR		FRANKIE GEAR WORKS INC.	
16	16	16	GM441	CLOSED END NEEDLE BEARING		TORRINGTON CO	
1	1	1	KA030BH3	BEAR. 1.6-DUPLEX HAYDON		KEENE CORP	
1	1	1	KA030AH3	BEARING-HAYDON		KEENE CORP	
	1	1	P70-2-24	ANTI BACK-LASH PINION		PIC DES CORP	
	1	1	BOURNS 3707	POTENTIOMETER	10 TURNS	BOURNS INC.	3
1	1	1	RES 3156046-005	EXTERNAL BEARING HOUSING			
1	1	1	RES3156036-017	PRELOAD NUT			
	1		RES 3156036-015	YAW BRACKETT			
1			RES3156046-003	GEAR OUTER SINGLE			
	1	1	RES3156046-001	GEAR, OUTER SHELL			
1	1	1	RES3156036-009	GUT ASSY.			
1			RES3156035-029	MOT-GEN-BRAKE ASSY			
	1		RES 3156035-019	MOT GEN BRAKE ASSY			
		1	RES 3156035-009	MOTOR-GEN. ASSY.			
-029	-019	-009	-009	WRIST DRIVE ASSY.			

QUANTITY / DASH NO — PART NO — ZONE — DESCRIPTION — STOCK SIZE — MATERIAL OR VENDOR — MATERIAL SPECIFICATION — FINISH OR MFR CODE

ODD DASH NO SHOWN — EVEN DASH NO OPP — LIST OF MATERIAL

-029	RES3156046-029
-019	RES3156046-019
-009	RES3156046-009

NEXT ASSY — USED ON — APPLICATION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND ARE AFTER PLATING

ZHNOSLABAR 0435 6-2-94

MARTIN COMPANY
DIVISION OF MARTIN MARIETTA CORPORATION

WRIST DRIVE ASSEMBLY— FFTS' MANIPULATOR ARM

38597 | D | RES 3156045

SCALE FULL — SHEET 1 OF 1

RES3156045

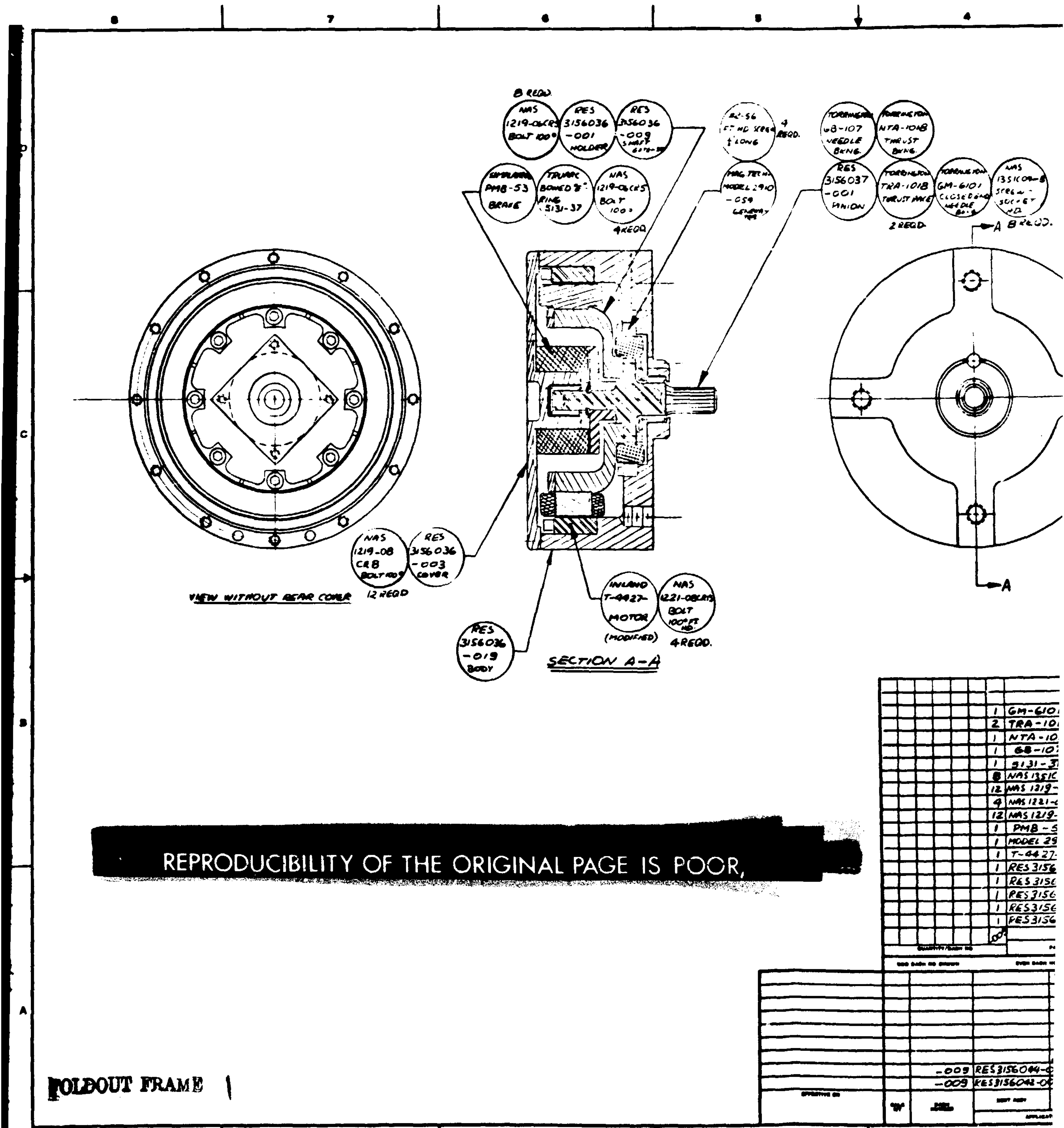
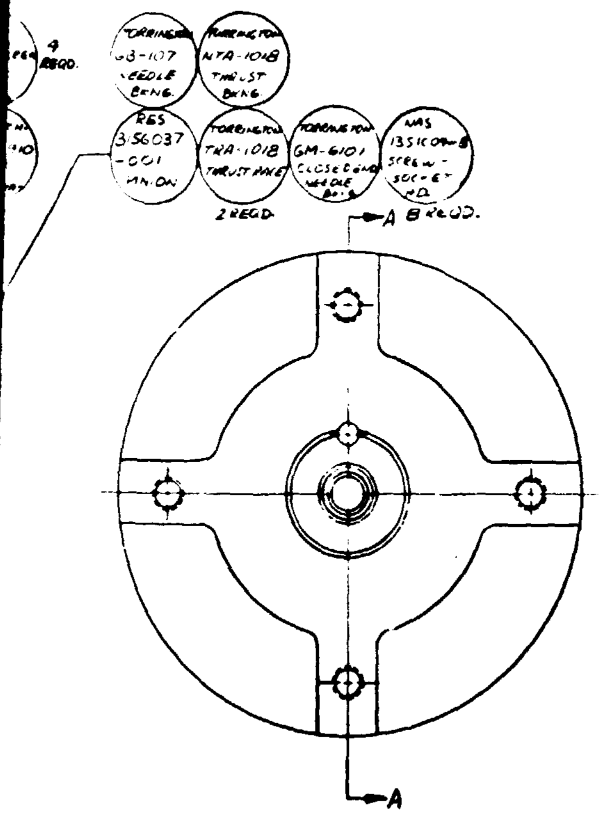


Figure VII-6 Moto -Generator-Brake Assembly of Shoulder and Elbow Drives



NOTES: 1. SEE DISCUSSION FOR MATERIAL SELECTION AND LUBRICATION OF SHAFTS, GEARS & BEARINGS.
2. USE "LOCKTIGHT" ON BOLTS & SCREWS

LIST OF MATERIAL

QUANTITY/DASH NO	PART NO.	DESCRIPTION	STOCK SIZE	MATERIAL OR VENDOR	MATERIAL SPECIFICATION	
1	GM-6101	NEEDLE BEARING	CLOSED END	TORRINGTON CORP		
2	TRA-1018	THRUST RACE		↕		
1	NTA-1018	THRUST BEARING		↕		
1	68-107	NEEDLE BEARING		TORRINGTON CORP		
1	5131-37	BOWED "E" RING	3/8" SHAFT	TRUARC-WALDES		
8	NAS 1351C08-8	SCREW-SOCKET HD.				
12	NAS 1219-06CR5	BOLT 100° FLUSH				
4	NAS 1221-08CR13	BOLT 100° FLUSH				
12	NAS 1219-08CR8	BOLT 100° FLUSH				
1	PMB-53	BRAKE	5 IN-LB	FORMSPRAG-SIMPLATROL		
1	MODEL 2910-054	GENERATOR		MAGNETIC TECHNOLOGY		
1	T-4427- SPEC.	MOTOR-PANCAKE	28 VDC.	INLAND MOTOR CORP.		
1	RES 3156037-001	PINION-SPECIAL	32 PITCH, 16 TEETH	20° P.A., 4340 STEEL OR EQUIVALENT		Q-12,
1	RES 3156036-009	SHAFT-MOTOR				
1	RES 3156036-001	HOLDER-MOTOR				
1	RES 3156036-003	COVER-MOTOR				
1	RES 3156036-019	BODY ASSY.				
009	-009	MOT-GEN-BRAKE ASSY				

NEXT ASSY	USED ON	QTY
-009	RES 3156044-009	1
-009	RES 3156042-009	1

DRAWN BY: JANOS LAZAR 0435 6-6-74

MARTIN MARIETTA CORPORATION
POST OFFICE BOX 179 DENVER COLORADO 80201

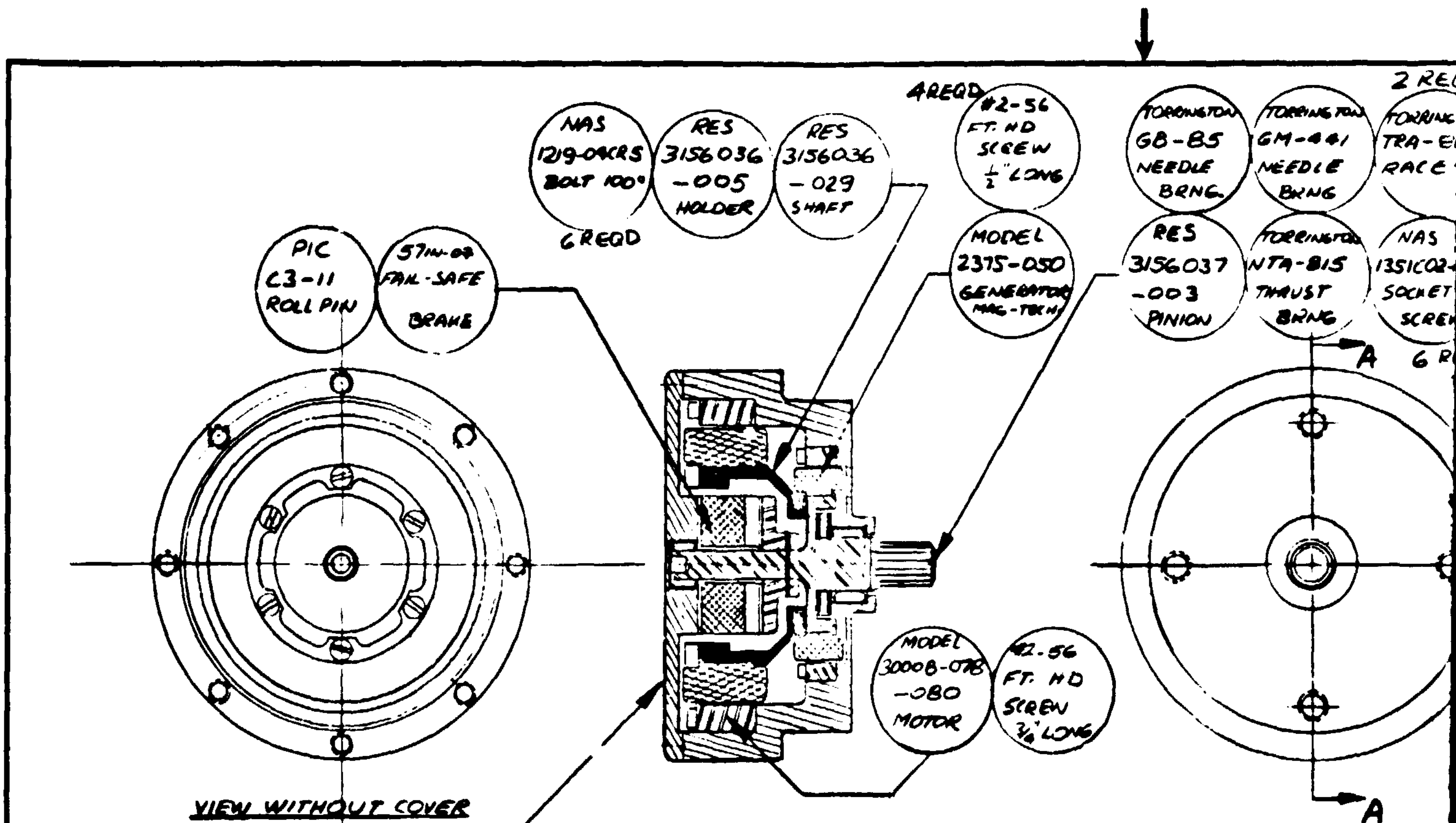
MOTOR-GENERATOR-BRAKE ASSEMBLY OF SHOULDER & ELBOW DRIVES.

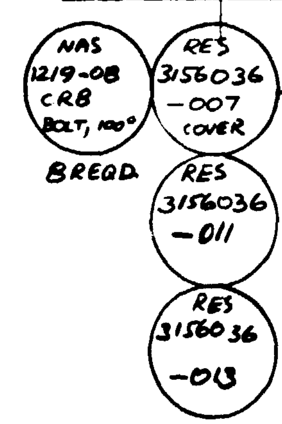
SIZE	CODE IDENT NO	
D	04236	RES 3156038

SCALE: FULL SHEET 1 OF 1

RES 3156038

FOLDOUT FRAME 2





QUANTITY-DASH NO -029	-019	-009	PART NO	ZONE	DESCRIPTION	
1			RES3156036-013		MOTOR COVER (ROLL)	
	1		RES3156036-011		MOTOR COVER (YAW)	
4	4	4	#2-56-3/4" LONG		FLAT HD. SCREW 82°	
4	4	4	#2-56-1/2" LONG		FLAT HD. SCREW 82°	
1	1	1	C3-11		ROLL PIN	
2	2	2	TRA-815		RACE	
1	1	1	NTA-815		NEEDLE THRUST	
1	1	1	GM-441		NEEDLE BRNG CLOSED END	
1	1	1	GB-85		NEEDLE BEARING	
6	6	6	NAS1351C02-6		SOCKET HD. SCREW	
6	6	6	NAS1219-04CRS		BOLT, 100° FLUSH	
8	8	8	NAS1219-08CRB		BOLT, 100° FLUSH	
1	1	1	MBF12-28-C-2-B		BRAKE	
1	1	1	MODEL 2375-050		GENERATOR	
1	1	1	MODEL 3000B-078-080		MOTOR	28 V
1	1	1	RES3156037-003		PINION-SPECIAL	40 PIT
1	1	1	RES3156036-029		SHAFT, MOTOR	
1	1	1	RES3156036-005		HOLDER, MOTOR	
		1	RES3156036-007		COVER, MOTOR (PITCH)	
1	1	1	RES3156036-039		BODY ASSY	
029	019	009			MOT-GEN-BRAKE ASSY	

ODD DASH NO SHOWN — EVEN DASH NO OPP — LIST OF MATE

DASH NUMBER	NEXT ASSY	USED ON	FINAL ASSY
-029	RES3156045-029		1
-019	RES3156045-019		1
-009	RES3156045-009		1

EFFECTIVE ON — CALC WT — APPLICATION — QTY REQD

DIMENSIONING REF MIL-STD-8
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES AND ARE AFTER PLATING
TOLERANCES ON

FRACTIONS	DECIMALS .X	.XX	.XXX	ANGLES
± 1/32	± .1	± .03	± .010	± 1/2°

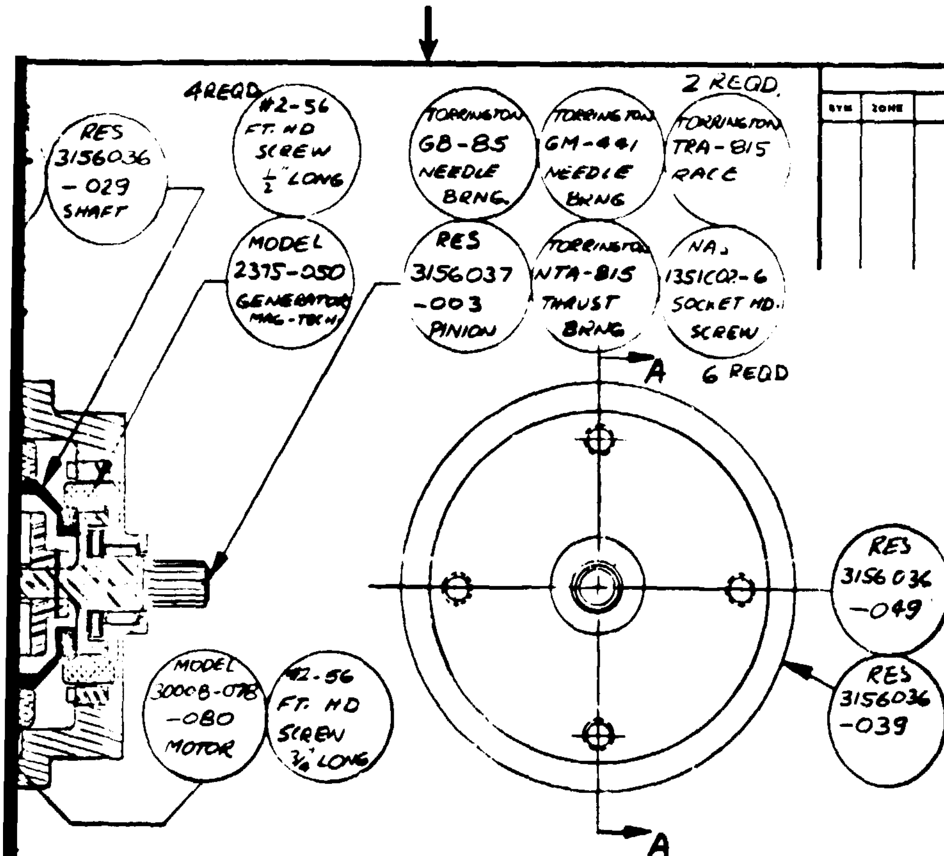
MACHINED SURFACES REF MIL-STD-10 ✓

MIL-I-8500 STATUS
INTERCHANGEABLE
REPLACEABLE
UNCONTROLLED

FOLDOUT FRAME

1

Figure VII-7 Motor-Generator-Brake Assembly of Wrist Drive



REVISIONS				
SYM	ZONE	DESCRIPTION	DATE	APPROVED

NOTES: 1. SEE DISCUSSION ON MATERIAL SELECTION AND LUBRICATION OF SHAFTS, GEARS, BREARINGS & COMMUTATORS.
2. USE "[illegible]TIGHT" ON BOLTS & SCREWS.

QTY	PART NO	ZONE	GEN SYM	DESCRIPTION	STOCK SIZE	MATERIAL OR VENDOR	ISSUE CONF	MATERIAL SPECIFICATION	FINISH OR MFR CODE	CHG
	RES 3156036-013			MOTOR COVER (ROLL)						
	RES 3156036-011			MOTOR COVER (YAW)						
4	#2-56 - 3/4" LONG			FLAT HD. SCREW 82°						
4	#2-56 - 1/2" LONG			FLAT HD. SCREW 82°						
1	C3-11			ROLL PIN		PIC DES CORP.				
2	TRA-815			RACE		TORRINGTON				
1	NTA-815			NEEDLE THRUST						
1	GM-441			NEEDLE BRNG CLOSED END						
1	GB-85			NEEDLE BEARING		TORRINGTON				
6	NAS 1351C02-6			SOCKET HD. SCREW						
6	NAS 1219-04CR5			BOLT, 100° FLUSH						
8	NAS 1219-08CR8			BOLT, 100° FLUSH						
1	MBF 12-28-C-2-B			BRAKE		VERNITRON CORP.				
1	MODEL 2375-050			GENERATOR		MAGNETIC TECHNOLOGY				
1	MODEL 3000B-078-080			MOTOR	28 VDC.	MAGNETIC TECHNOLOGY				
1	RES 3156037-003			PINION-SPECIAL	40 PITCH, 15 TEETH, 20° PA, 9310 STEEL OR EQUIV. Q-12, STRAIGHT TEETH.					
1	RES 3156036-029			SHAFT, MOTOR						
1	RES 3156036-005			HOLDER, MOTOR						
1	RES 3156036-007			COVER, MOTOR (PITCH)						
1	RES 3156036-039			BODY ASSY						
	-009			MOT-GEN-BRAKE ASSY						

EVEN DASH NO OPP

LIST OF MATERIAL

NEXT ASSY	USED ON	FINAL ASSY	TEST
RES 3156045-029		1	
RES 3156045-019		1	
RES 3156045-009		1	
APPLICATION		QTY REQD	

DIMENSIONING REF MIL STD 8
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES AND ARE AFTER PLATING
TOLERANCES ON

FRACTIONS	DECIMALS X	.XX	.XXX	ANGLES
± 1/32	± .1	± .03	± .010	± 1/2°

MACHINED SURFACES REF MIL-STD-10 ✓

MIL-I-8500 STATUS
INTERCHANGEABLE
REPLACEABLE
UNCONTROLLED

DRAWN BY JANOS LAZAR DEPT 0435 DATE 6-7-74
CHECKER
STRESS ENGR
WT ENGR
MATL ENGR
RELIABILITY
GR ENGR
PROJECT
CUST APPROVAL

MARTIN MARIETTA CORPORATION
POST OFFICE BOX 179, DENVER, COLORADO

MOTOR-GENERATOR-BRAKE ASSEMBLY OF WRIST DRIVE.

SIZE C CODE IDENT NO 04236 RES 3156035

SCALE FULL SHEET 1 OF 1

The contact stress formula for gear mesh, based upon D. W. Dudley: Practical Gear Design, McGraw Hill Co., 1954, is given by:

$$S_c = \sqrt{\frac{0.70}{\left(\frac{1}{E_1} + \frac{1}{E_2}\right) \cos \phi \sin \phi}} \sqrt{\frac{W}{Fd} \left\{ \frac{m_G + 1}{m_G} \right\}}$$

where:

E_1 = modulus of elasticity of the pinion (30×10^6 psi)
E_2 = modulus of elasticity of the gear (30×10^6 psi)
ϕ = normal pressure angle (20°)
W = tangential driving pressure in pounds.
F = face width in inches
d = the pitch diameter of the pinion
m_G = gear to pinion ratio

Substituting the above numbers for steel gears and pinions, the contact stress formula simplifies to:

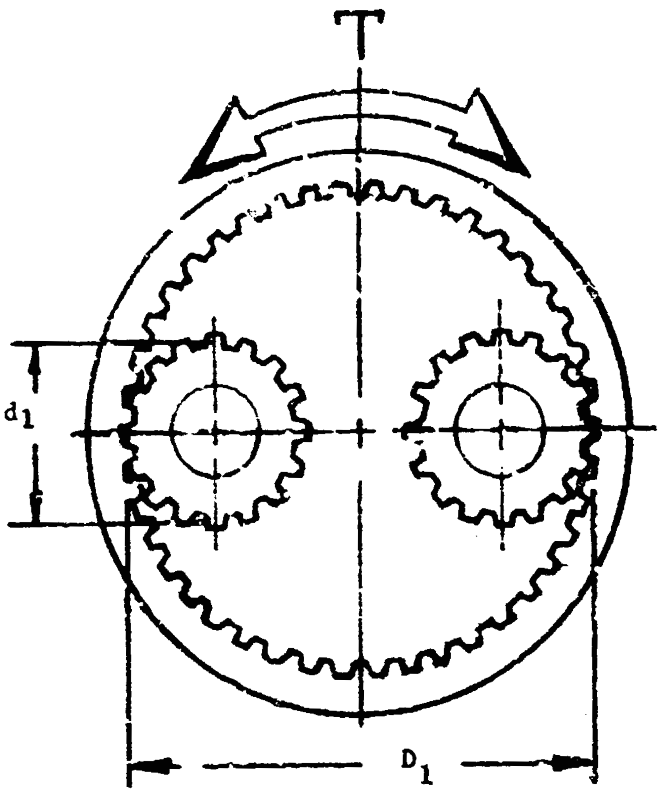
$$S_c = 5715 \sqrt{\frac{W}{Fd} \left\{ \frac{m_G + 1}{m_G} \right\}}$$

This formula was used in the gear design.

b. <u>Sample Gear Train Design</u> - The four branch gear train acts like a "planetary" gear system at the output, but the gear train acts as a simple spur gear reduction which has high efficiency, either as a speed reducer or as a speed increaser. Furthermore, it can be adjusted to the control system backlash requirements.

After a number of iteration stages, the final empirical calculation procedure for the manipulator elbow drive is shown in Fig. VII-8. Note that both stresses are within tolerable limits (< 140,000 psi). Therefore, the first mesh is acceptable. The procedures to calculate

Elbow Drive Joint



T = torque output or input of ring gear

= 49 ft-lb

d_1 = pitch diameter of pinion

D_1 = pitch diameter of internal ring gear

First Mesh Ratio:

$$m_{G_1} = \frac{D_1}{d_1} = \frac{4.25}{.812} = 5.23$$

Pinion Torque:

$$\frac{49/2}{5.23 \times .97} = 4.86 \text{ ft-lb}$$

Normal Tooth Load on Pinion =

$$W = \frac{4.86 \times 12}{.812/2} = 143 \text{ lbs}$$

Bending Stress on Pinion Tooth (Ref. 18)

$$S_B = \frac{W}{Fy\ CP}$$

where:

$$CP = \frac{\pi}{DP} = \frac{\pi}{16} = .196 \text{ and}$$

y = .083 for 20° P.A. 13 teeth

$$S_B = \frac{143}{.625 \times .083 \times .196} = 14,000 \text{ psi}$$

$$\text{Contact Stress} = S_c = 5715\sqrt{\frac{W}{Fd}\left\{\frac{m_G + 1}{m_G}\right\}} = 104,800 \text{ psi}$$

Figure VII-8 Elbow Drive Joint Calculations the next two meshes are similar. As a result of these calculations, the following gear ratios are incorporated into the preliminary design:

Shoulder Joints:	50:1
Elbow Joint:	30:1
Wrist Joints:	42.6:1

c. Center Distance Considerations - Due to the severe space environmental conditions and the resulting differential thermal expansion of the gear housing with respect to the gear center, the center distances must be set "loose" to prevent cogging and lock up of the gears. The worst case condition occurs when the gear shaft housing structure is heated up and the outer shell and ring gear are at a cold temperature condition. Therefore, the center distance, C_D, must be set at:

$$\text{Center Distance Increase} = \Delta C_D = + C_D \Delta T \times C_T$$

where:

C_T = coefficient of linear thermal expansion

ΔT = maximum temperature differential expected

Care must be exercised during the detail design phase and the material selection should be made with careful considerations of this ΔC_D.

d. Lubrication - As discussed in Section V, the lubricant selected for the gears was "Hi-T". While the lubricant thickness must be established during the manipulator detailed design phase, it is recommended at this time the thickness should be in the 0.0001" to 0.0005" range for best results. Note that the contact stress levels of the gear trains were well below the 140,000 psi "safe" operational region of this lubricant.

e. Summary - Table VII-1 presents a summary of the joint gear designs.

Table VII-1 Gear Design Summary; Shoulder Joint

Mesh No.	Pinion (d) Pitch Dia / No. of Teeth	Mating Gear Pitch Dia Per No. of Teeth	Gear Ratio m_G	$\frac{m_G + 1}{m_G}$	Mesh Efficiency (Est) %	Normal Tooth Load in Pounds	Face Width of Gear (F) Inches	Fd (Inch)^2	T/2 Pinion Torque Ft-lb	Pinion Tooth Bending Stress PSI	Contact Stress (Hertz Str.) PSI
1S	1.0/12	5.5/66	5.5	1.18	97	202	.75	.75	8.45	13,200	102,000
2S	.625/10	1.75/28	2.8	1.35	97	115.5	.625	.391	3.35	14,700	114,000
3S	.50/16	1.625/52	3.25	1.30	97	44.5	.375	.187	.93	12,900	101,000
									Elbow Joint		
1E	.812/13	4.25/68	5.23	1.19	97	143	.625	.507	4.86	10,200	104,800
2E	.65/13	1.65/33	2.54	1.39	97	76.3	.437	.284	2.06	13,420	115,500
3E	.50/16	1.25/40	2.50	1.40	97	41	.312	.156	0.86	14,100	110,000
									Wrist Joint		
1W	.50/12	3.0/72	6.0	1.167	97	60	.50	.25	2.5	11,850	96,000
2W	.375/12	1.0/32	2.66	1.38	97	30	.375	.14	1.02	10,500	97,800
3W	.375/15	1.0/40	2.56	1.38	97	12.4	.187	.0705	.39	9,200	89,200

2. Motor Selection

Prior to the selection of a motor, typical catalog motors were an. yzed to establish an approximate "state-of-the-art" motor weight characteristic. It was found, as a rule of thumb for the larger diameter motors, i.e. $\leq$ 7.6 cm (3"), that the motor weight in pounds is numerically equal to the motor peak torque in ft-lbs. This relationship provided a basis for estimated weights prior to the selection of a specific motor.

In addition, it should be recognized that any optimization of motors based upon the gear ratio is somewhat superficial as the unloaded arm presents inertia loads of at least an order of magnitude greater than the reflected motor inertia.

a. Shoulder Yaw and Pitch Actuators - The selection of the shoulder actuators was based upon the following considerations:

Gear Ratio, N: $\leq 50:1$
Output Torque, T_D: 90 ft-lbs (at 0 - 0.2 rad/sec)

The minimum motor torque required, as. .ng 90% efficiency, is given by:

$$\text{Input Torque, } T_i = T_o/0.9\, N \Big|_{N=50} = 384 \text{ oz-in}$$

The speed torque product is equivalent to 24.5 watts. Therefore,

Shaft Power, P_s: 24.5 watts

and the required motor rating is 109 watts. The desired no load speed is approximately 25 rad/sec with a 50:1 gear ratic.

The physical characteristics of the motor, based upon the manipulator size requirements, are:

Outside Diameter, O.D. = ≤ 15.2 cm (6 in)

Inside Diameter, I.D. = > 5.1 cm (2 in)

Weight: ≤ 1.36 kg (3 lbs)

For comparative purposes, typical "off-the-shelf" motors for application to the shoulder have been summarized in Table VII-2. From weight and power considerations, the Inland model T-4427 was selected as a representative candidate. Note that this motor will be used in a derated application for two reasons: (1) reduced power consumption and (2) increased allowable duty cycles.

A preliminary analysis based on thermal considerations and assuming convection characteristics of a 1-g environment establishes an approximate duty cycle. The motor specification indicates a temperature rise of 1.8°C/watt with an allowable temperature rise of 105°C. (155°C models are available per special request.) Therefore, a conservative estimate of continuous power is given by 105/1.8 or 58.3 watts. At this power rating, 445 oz-in of continuous torque is supplied by the motor. This value of torque exceeds the 384 oz-in maximum torque required at the manipulator shoulder.

The power required by the motor at the 384 oz-in stall torque level is:

$$P = (T/K_m)^2 = (384/58.8)^2 = 42.6 \text{ watts}$$

The current required is:

$$I = T/K_T = 384/82.5 = 4.65 \text{ amps}$$

The maximum voltage is given by:

$$V_m = K_B\omega + IR_M = (0.58)(10) + (4.65)(2) = 15.1 \text{ volts}$$

Thus, this same motor, designed for a higher voltage rating is desirable. With the FFTS supply of 28 $\pm$ 4 volts, a V_m of at least 24

Table VII-2 Typical Shoulder Motor Types*

Parameter Model Number	Peak Torque T_p (in-oz)	Power at T_p P_p (watts)	No Load Speed ω_{nl} (rad/sec)	Weight (oz)	Motor Constant K_m (in-oz/ watts)	Torque Sensitivity K_T (in-oz/amp)	Voltage at T_p V_p (volts)	Watts Required at 384 (in-oz)	Outside Diameter O.D. (in)	Inside Diameter I.D. (in)	Width W (in)
5125-110	400	96	32	48	40.8	92.8	22.1	80	5.126	2.390	1.100
2970-800	480	412	110	92	23.7	40.9	34.6	280	2.070	0.250	8.000
5125-160	700	136	26	83	60.0	116.0	22.6	40	5.126	2.390	1.600
MT-2927	384	125	45	32	-	80.6	26.0	125	3.730	1.640	1.338
MT-2921	461	111	34	54.5	-	73.0	17.7	-	3.730	1.500	2.078
MT-2970	557	211	57	96	-	89.3	34.1	-	3.730	1.313	2.6[illegible]
T-4076	691	127	27	89.5	-	148.0	27.7	-	5.125	2.390	1.750
T-4427	865	216	36	48	58.8	82.5	21.0	42.6	5.125	3.500	1.525
T-5134	519	85	22	77	56.2	182.5	28.7	-	6.252	2.391	1.312
T-5406	334	52	19	48	-	192.0	26.0	52	6.125	4.500	1.168

* Inland and Magtech Models with Range of 400-865 in-oz (2-4.5 ft-lbs)

volts is desirable and will reduce the current required. Table VII-3 shows the relationship between the catalog motor, T-4427 and a modified 33.4 volt model.

Table VII-3 Modified T-4427 Characteristics

Parameter	T-4427	Modified
Voltage, V_p (volts)	21.0	33.4
Resistance, R_m (ohms)	2.0	5.06
Current at T_p, I_p (amps)	10.5	6.6
Torque Sensitivity, K_T (oz-in/amp)	82.5	131
Back E.M.F., K_B (volts/rad/sec)	0.58	0.913

For the modified T-4427, the current, voltage, and power required to provide 384 oz-in of stall torque become:

$$I_{max} = I_{stall} = 384/131 = 2.93 \text{ amps}$$

$$V_{stall} = IR_m = (2.93)(5.06) = 14.8 \text{ volts}$$

$$P_{stall} = I^2R = (2.93)^2 (5.06) = 43.5 \text{ watts}$$

The maximum control voltage is

$$V_m = K_B\omega + IR_m = (0.913)(10) + (2.93)(5.06) = 24 \text{ volts}$$

and the maximum peak power required is

$$P_m = I_m V_m = (2.93)(24) = 70.3 \text{ watts}$$

The peak power of 70.3 watts consists of approximately 43.5 watts of I^2R losses and 24.5 watts, based on a 90% efficient system, delivered to the output shaft.

A torque-speed diagram of the shoulder actuators is illustrated in Fig. VII-9. Both the basic motor and the actuator ($N = 50$) characteristics are shown with the typical operating region indicated.

b. Elbow Pitch Actuator - The selection of the elbow actuator was based upon the following considerations:

Gear Ratio, $N = \leq 50:1$
Output Torque, T_o: 50 ft-lbs (at 0 - 0.4 rad/sec)

Three options were considered in the selection process: (1) Use the shoulder actuator "as-is" with a gear ratio of 50:1 in which the overall actuator diameter and weight are excessive but a significant power advantage is obtained, or (2) use the same motor but pick a different gear ratio based upon the possibility of a weight reduction, or (3) select a completely different motor and gear ratio. Option 2 was selected to provide commonality within the manipulator motors while recognizing that a small weight savings might be realized using Option 3.

Therefore, the motor type baselined for the elbow actuator was the modified Inland Model T-4427.

The speed-torque product is equivalent to 27.2 watts. Therefore,

Shaft Power, P_s: 27.2 watts

and the required motor rating, again assuming a 90% efficiency, is 121 watts.

The minimum gear ratio for the elbow actuator was established using the characteristic equation of the T-4427 motor, given by

$$T = 865 - k\omega \quad \text{at } \omega = 36,\ T = 0; \quad \therefore k = 24$$

Using a gear ratio of N,

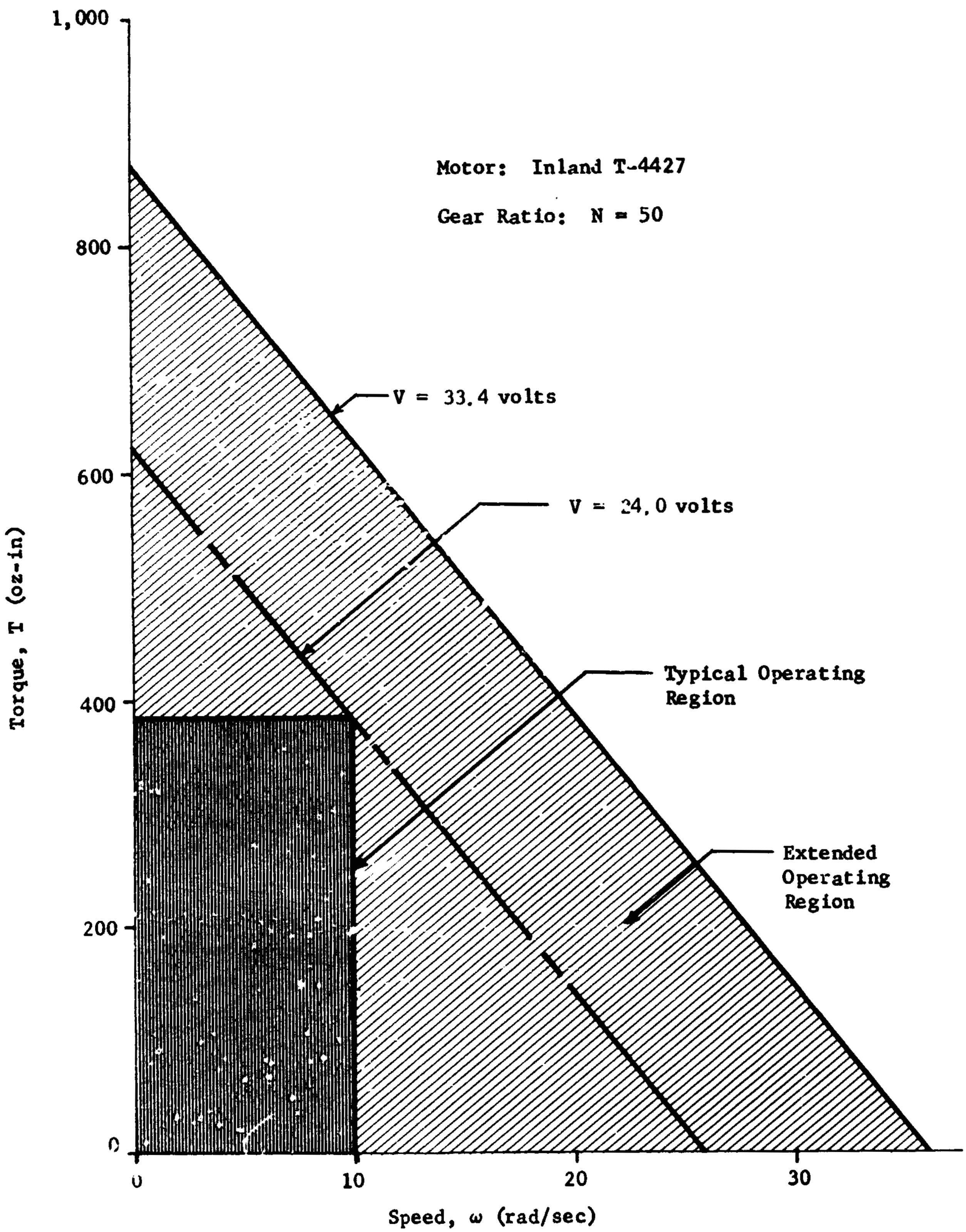


Figure VII-9 Shoulder Torque-Speed Characteristics

$$T = 865 \cdot N - 24 \cdot \omega/N$$

The boundary conditions for the solution are

at $T = 9{,}600$ oz-in, $\omega = 0.4$ rad/sec.

Therefore,

$$9{,}600 = 865\ N - 24\ (0.4)/N$$

or $N_{min} \approx 11$

Recognizing that, by using the largest value of N, the overall power requirements are reduced, mechanical design considerations (size, weight, and complexity) led to the selection of N = 30 for the manipulator elbow gear ratio.

Calculations for the elbow actuator are as follows:

Input Torque, $T_i = T_o/0.9\ N \Big|_{N=30} = 356$ oz-in

Maximum Current, $I_{max} = I_{stall} = T_i/K_T = 356/131 = 2.72$ amps

Voltage at Stall $= I_m R_m = (2.72)(5.06) = 13.75$ volts

Power at Stall $= (I_{stall})^2\ R_m = (2.72)^2\ (5.06) = 37.4$ watts

The maximum control voltage is

$$V_m = K_B \omega + IR_m = (0.913)(12) + (2.72)(5.06) = 24.8 \text{ volts}$$

and the maximum peak power required is

$$P_m = I_m V_m = (2.72)(24.8) = 67.5 \text{ watts}$$

The peak power of 67.5 watts consists of approximately 37.4 watts of I^2R losses and 27.2 watts, based upon a 90% efficient system, delivered to the output shaft.

A torque-speed diagram of the elbow actuator is illustrated in Fig. VII-10.

c. <u>Wrist Pitch, Yaw, and Roll Actuators</u> - The selection of the wrist actuators was based upon the following considerations:

Gear Ratio, N: $\leq$ 45:1
Output Torque, T_o: 15 ft-lbs (at 0 - 0.2 rad/sec).

The minimum torque required, assuming 90% efficiancy, is given by:

$$\text{Input Torque, } T_i = T_o/0.9\,N \Big|_{N = 45} = 71.2 \text{ oz-in.}$$

The speed-torque product is equivalent to 4.08 watts. Therefore,

Shaft Power, P_s: 4.08 watts

and the required rating of the motor is 18.2 watts. The desired no load speed is approximately 22.5 rad/sec with a 45:1 gear reduction.

The physical characteristics of the motor, based upon the manipulator size requirements, are:

Outside Diameter, O.D. = 8.25 cm (3.25 in) maximum
Inside Diameter, I.D.: 3.8 cm (1.50 in) minimum
Weight: $\leq$ 0.45 kg (1 lb)

Again, for comparative purposes, typical "off-the-shelf" motors were evaluated for application to the wrist actuators. As summarized in Table VII-4, it was noted that, in general, the smaller motors were not available with a low no load speed ($\approx$ 22.5 rad/sec) as desired and hence provide minimum power. Conversations with motor vendors

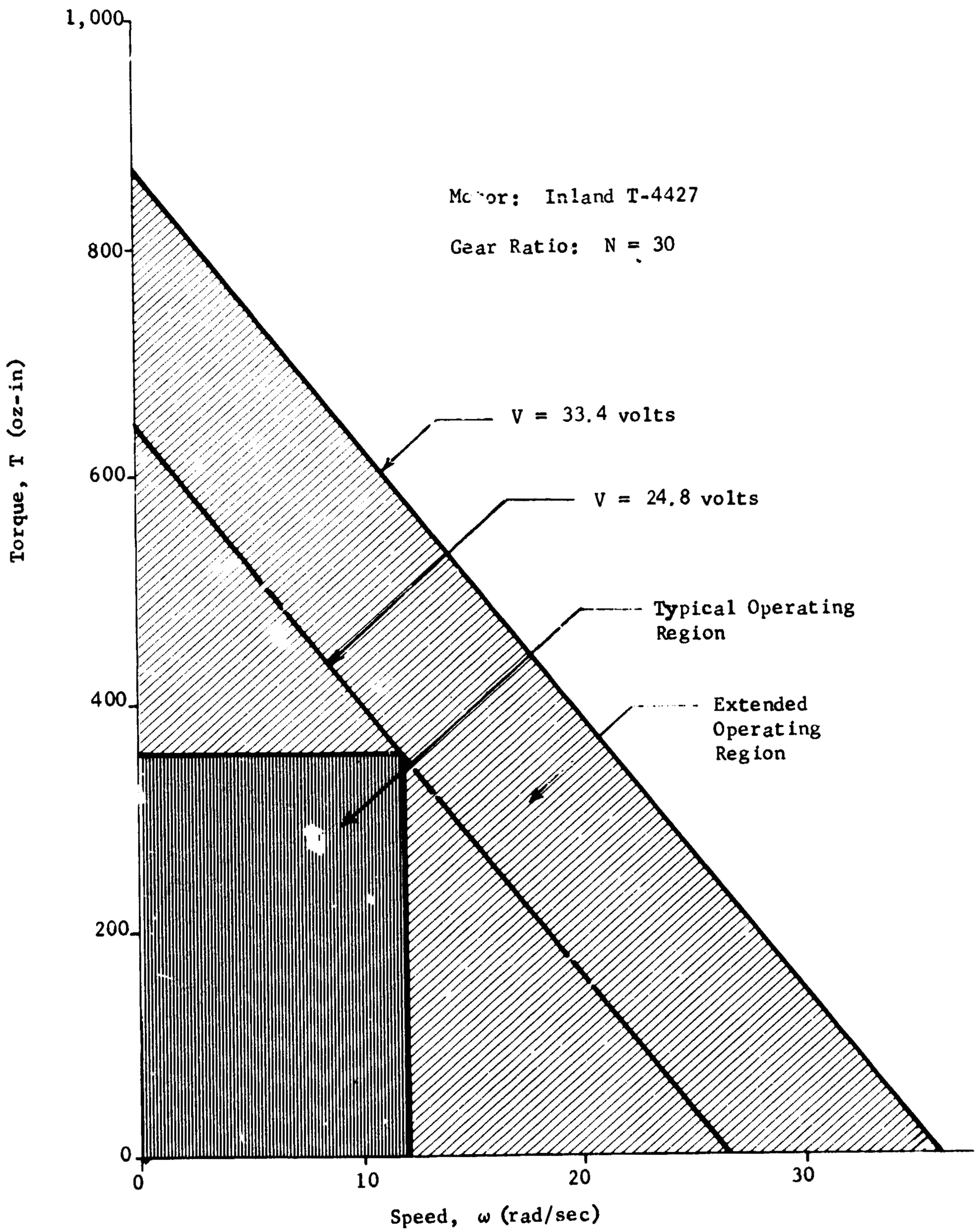


Figure VII-10 Elbow Torque Speed Characteristics

Table VII-4 Typical Wrist Motor Types

Parameter / Model Number	Peak Torque T_p (oz-in)	Power at T_p P_p (watts)	No Load Speed ω_{nl} (rad/sec)	Weight (oz)	Motor Constant K_M (in-oz/ watt)	Torque Sensitivity K_T (in-oz/amp)	Voltage at T_p V_p (volts)	Watts Required at 71.2 (oz-in)	Outside Diameter O.D. (in)	Inside Diameter I.D. (in)	Width W (in)
2813-100	90	42	60	18.0	13.9	54.2	24.9	25	2.813	1.000	1.000
2910-064	90	80	120	9.2	10.0	28.9	25.8	58	2.910	1.600	0.640
3000B-065	90	58	86	8.7	11.8	39.0	25.2	35	3.000	1.750	0.650
NT-1308	90	255	407	16.4	-	7.8	22.0	-	1.938	0.625	1.860
NT-1328	90	110	170	30.0	-	18.0	22.0	-	1.938	0.500	2.295
T-2209	90	47.5	75	18.0	-	53.7	28.4	-	2.813	1.000	1.000
T-1919	89	72	115	13.0	-	35.0	28.5	-	2.343	1.200	1.250
3000B-078	120	80	89	10.5	13.4	39.6	26.1	28.1	3.000	1.750	0.780
2910-100	145	61	56.4	15.2	18.6	61.6	25.8	1.8	2.910	1.600	1.000

did indicate that a lower no load speed could be achieved at the expense of increased weight and volume.

For preliminary design purposes, the Magtech Model 3000B-078 was selected as it provided the best compromize between weight and power.

Assuming the characteristics of this motor, two additional calculations were made to establish the thermal, as related to duty cycle, and power requirements of the motor used in a derated condition. The motor specification indicates a temperature rise of 2.5°C/watt with an allowable temperature rise of 130°C. (basically a 155°C model) Therefore, the allowable continuous power is given by 130/2.5 or 52 watts. At this rating, 96.6 oz-in of continuous torque is supplied by the motor. This value of torque exceeds the 71.2 oz-in maximum torque required at the manipulator wrist.

The power required by the motor at the 71.2 oz-in stall torque level is:

$$P = (T/K_m)^2 = (71.2/13.4)^2 = 28.1 \text{ watts}$$

The current required is:

$$I = T/K_T = 71.2/39.6 = 1.8 \text{ amps}$$

The maximum control voltage is given by:

$$V_m = K_B\omega + IR_m = (0.28)(9) + (1.8)(8.6) = 18 \text{ volts}$$

if the -080, 26.1 volt, model is implemented. However a model with a higher voltage rating such the -130 or -170 is recommended to reduce the maximum current requirement to ≈ 1.5 amps and increase the voltage to over 24 volts.

The peak power required is

$$P_m = I_m V_m = (1.8)(18) = 32.4 \text{ watts}$$

This peak power of 32.4 watts consists of approximately 28 watts of I^2R losses and 4.08 watts, based upon a 90% efficient system, delivered to the output shaft.

A torque-speed diagram of the wrist actuators is shown in Fig. VII-11 and illustrates the desire to reduce the no load speed of the motor to c[illegible] power consumption.

Table VII-5 below summarizes the "worst case" actuator power requirements. These conditions exist only when all actuators are required to deliver their maximum torque simultaneously. Task timeline data is required to establish an average value. However, less than 50 watts [illegible] expected.

Table VII-5 Actuator Power Requirements

		Peak Stall (watts)	Peak Operating (watts)
Shoulder:	Yaw	43.5	70.3
	Pitch	43.5	70.3
Elbow:	Pitch	37.4	67.5
Wrist:	Pitch	28.1	32.4
	Yaw	28.1	32.4
	Roll	28.1	32.4
Maximum:		208.7	305.3

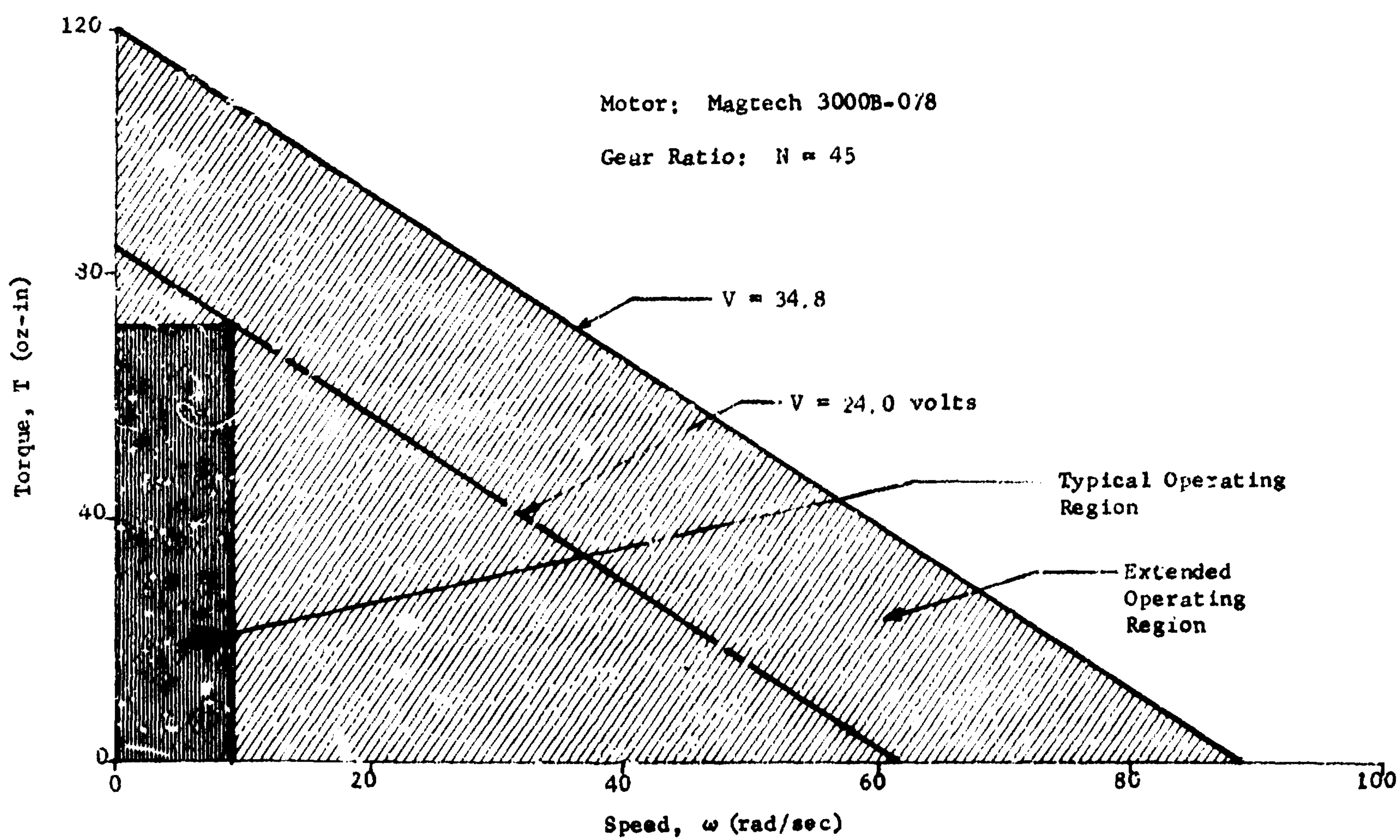


Figure VII-11 Wrist Torque-Speed Characteristics

3. **Bearing Selection**

Special attention was focused on the selection of the bearings. Three different kind of bearings are used in the preliminary design: angular contact; needle roller; and needle thrust. Whenever it was feasible during the design process, the needle rollers were employed. Because of their size and load carrying capability, they can be operated at a low level of Hertz stress. Their outer housing shell is case-hardended to .0004" thickness only and acts as a cushion for the needles such th the contact area per needle is increased and the contact stress is

All angular contact bearings utilize the duplex pair of bearings. Duplex bearings not only reduce the contact stresses but, at the same time, provide for accommodation of the high linear differential thermal expansion, or contraction, of the housing.

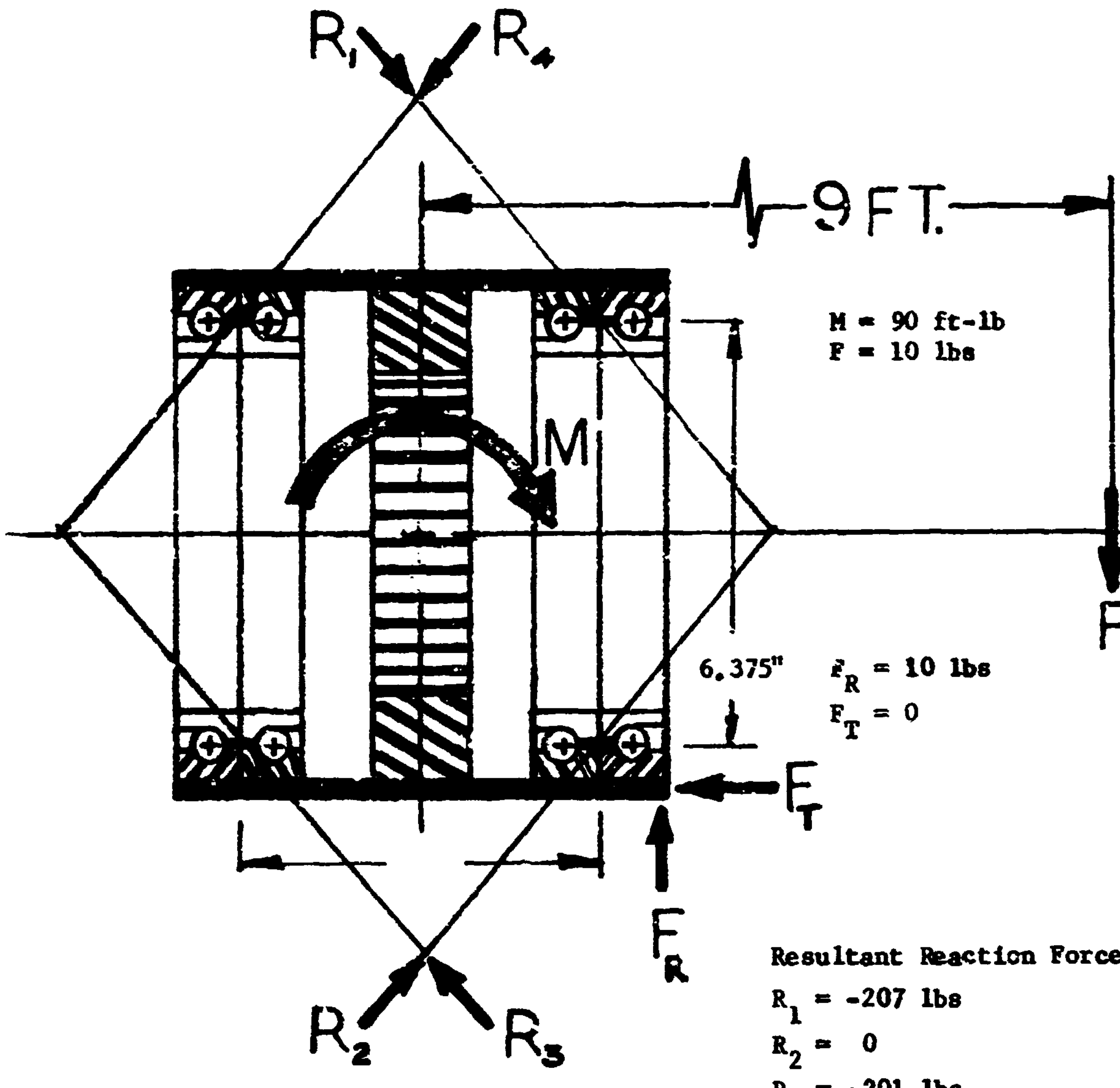
As an example, the reaction forces of the duplex angular contact bearings are analyzed below. The bearing loads were established for worst case conditions. Since the angular contact bearings are more sensitive to radial loads then to thrust loads, the pure radial condition was investigated for the maximum contact stress calculations.

As shown in Fig. VII-12, the four bearings share the 207 lb maximum radial load, V. Calculating the normal load, P_o, on one of the loaded balls, based upon "New Departure Engineering Data-Analysis of Stresses and Deflections, Vol. I and II", yields

$$P_o = \frac{4.37 \times V}{4 \times n} = \frac{4.37 \times 207}{4 \times 85} = 2.67 \text{ lbs/ball}$$

$$\frac{d \cos\beta}{E} = \frac{.156 \times .866}{6.375} = .0212 \text{ for } \beta = 30°$$

Using the reference data and chart for a bearing of 55% conformity, then the stress factor for the bearing race (fs_o) will be (from chart 47)



Resultant Reaction Forces:

R_1 = -207 lbs

R_2 = 0

R_3 = -201 lbs

R_4 = -5 lbs

where:

F_R = radial load

F_T = thrust load

n = 85 number of balls per bearing

d = .156" diameter of balls

Figure VII-12 Free Body Diagram of Shoulder Bearings

$$fs_i = 1.31$$

Substituting this into the contact stress formula:

$$Sm_i = 15079 \text{ fs } \left(\frac{P_o}{d^2}\right)^{1/3}$$

Then

$$Sm_i = 15079 \times 1.31 \times \left(\frac{2.67}{(.156)^2}\right)^{1/3} = 94,000 \text{ psi}$$

This applies for the inner race: the other race stress is slightly smaller. Therefore, the bearing design is within the contact stress requirements of $\leq 140,000$ psi.

Needle roller bearings were selected for the pinion shafts which also carry the gears (clustered). The worst case load is at the shoulder joint on the 1st stage needle bearing. The bearing selected was a GM-861 by Torrington Co.

An analysis shows that a load of 100 lbs maximum exists on the bearing. This amounts to about 38 lb/in maximum load, P_{max}, on a single roller. Using the formula given in S. Timoshenko, "Strength of Materials, Part II", the maximum stress is given by:

$$P_{max} = 0.59 \quad 2P' \frac{E_1E_2 \ (d_1+d_2)}{(E_1+E_2) \ d_1d_2}$$

Substituting,

$$E_1 = E_2 = 30 \times 10^6 \text{ psi}$$
$$d_1 = .0655''$$
$$d_2 = - .625$$

yields

$$P_{max} = 73,800 \text{ psi} \; (\leq 140,000 \text{ psi})$$

which again is within the contact stress requirements of the lubrication.

4. <u>Cable Routing and Wire Specifications</u>

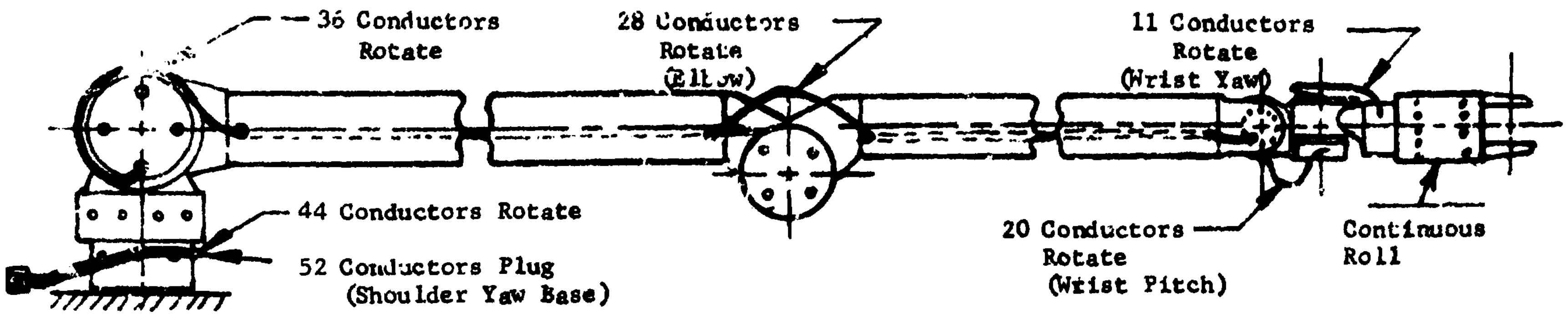
The wire cables are routed through joints whenever possible. The wire bundle is estimated to be about 5/8 inches in diameter at the shoulder and 1/2 inch at the elbow.

The wire specifications are summarized in Table VII-6. Note that a generous bend radius is recommended and insulation (e.g. teflon shield) should be provided such that the cable I^2R losses are used to provide heating of the cable bundle. These considerations will increase the number of allowable bending cycles by reducing the "rigidity" of the wire bundle under low temperatures.

5. <u>Mass Properties</u>

Table VII-7 summarizes the mass properties of the preliminary manipulator design.

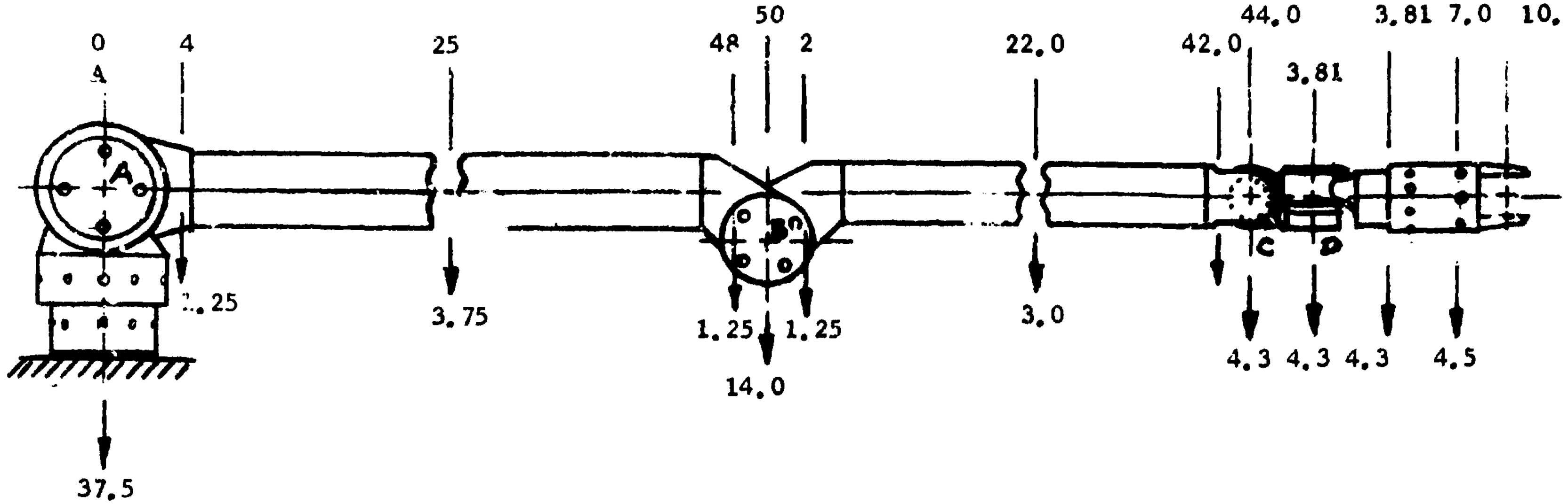
Table VII-6 Electrical Cable Routing and Wire Specifications



System/Joint	Function	No. Required	Gage No.	Subtotal No.
End Effector	Motor Drive	2 SH	22	2
Wrist Roll	Motor Drive	2 SH	22	
	Tachometer	2 SH	24	
	Brake	1 TW	24	
	Common	1 TW	18	
	Potentiometer	3 TW	24	
	Common	1 TW	20	12
Wrist Yaw	Motor Drive	2 SH	22	
	Tachometer	2 SH	24	
	Brake	1 TW	24	
	Potentiometer	3 TW	24	20
Wrist Pitch	Motor Drive	2 SH	22	
	Tachometer	2 SH	24	
	Brake	1 TW	24	
	Potentiometer	3 TW	24	28
Elbow Pitch	Motor Drive	2 SH	22	
	Tachometer	2 SH	24	
	Brake	1 TW	24	
	Potentiometer	3 TW	24	36
Shoulder Pitch	Motor Drive	2 SH	22	
	Tachometer	2 SH	24	
	Brake	1 TW	24	
	Potentiometer	3 TW	24	44
Shoulder Yaw	Motor Drive	2 SH	22	
	Tachometer	2 SH	24	
	Brake	1 TW	24	
	Potentiometer	3 TW	24	52

Notes: 2 SH = 2 Conductor Shielded
1 TW = 1 Conductor Twisted to Common
3 TW = 3 Conductor Twisted to Common

Table VII-7 Mass Properties



Component Name	M(A) In-Lb	M(B) In-Lb	M(C) In-Lb	M(D) In-Lb	Weight Lbs
End Effector	472	247	49.5	31.5	4.5
Roll Drive	434	222	32.0	16.0	4.3
Yaw Drive	420	205	16.0	--	4.3
Pitch Drive	404	189	--	--	4.3
Adapter	47	22	--	--	.5
Lower Tube	216	66	--	--	3.0
Elbow Adapter	65	2.5	--	--	1.25
Elbow Drive	700	--	--	--	14.00
Elbow Adapter	60	--	--	--	1.25
Upper Arm	94	--	--	--	3.75
Shoulder Adapter	6	--	--	--	1.25
Shoulder Pitch	--	--	--	--	18.00
Shoulder Yaw	--	--	--	--	18.00
Pitch-Yaw Adapt.	--	--	--	--	1.50
	2918	953.5	97.5	47.5	79.90

Cables and Accessories

4.0 Lbs Total

Total Weight of Arm

83.9 Lbs

B. CONTROL SYSTEM

As discussed in Section IV-C, the RAE/Rotation control mode has been selected for preliminary design. The technique utilizes a force to torque conversion for the translational degrees of freedom and incorporates the hawk mode and terminal device to range vector transformation equations. To reiterate, the prominent features of the spherical coordinate scheme are:

1. Simple equations, no matrix inversions needed.
2. Manipulator applied forces and moments visually displayed to the operator.
3. Variable servo stiffness permitting "free" gimbal motion.
4. Range, Azimuth, Elevation and X, Y, Z motion controllable in the spherical base and terminal device cartesian axis systems, respectively.
5. Easily servo compensated to accommodate large gain and inertia changes.

The control law equations and servo compensation network design for the six gimbal actuators are detailed below.

1. Control System Details

Fig. VII-13 depicts the complete RAE/Rotation control scheme. Signals received by the control system from the input rate controllers and gimbal sensors and computed information transmitted to the operator's console and joint actuators are detailed.

The coordinate transformation T derives $\dot{R}$, $\dot{A}$, and $\dot{E}$ values in the base axis system from the $\dot{\underline{X}}_c$ commands given in terminal device coordinates. This transformation used in conjunction with the rotational Hawk commands, $\dot{\theta}_{wh}$, $\dot{\phi}_{wh}$, $\dot{\rho}_{wh}$, provides cartesian control in the TD axis system.

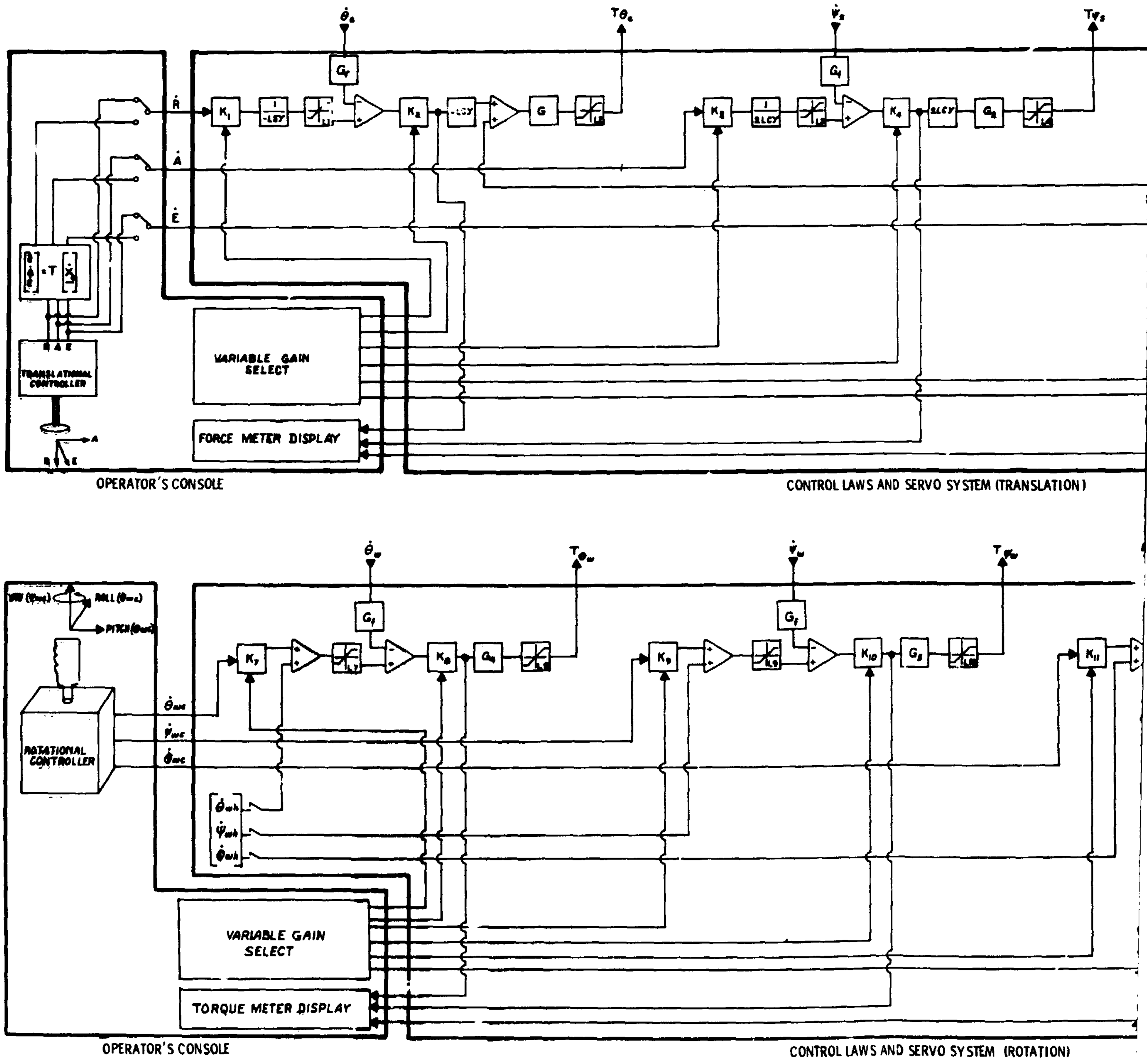
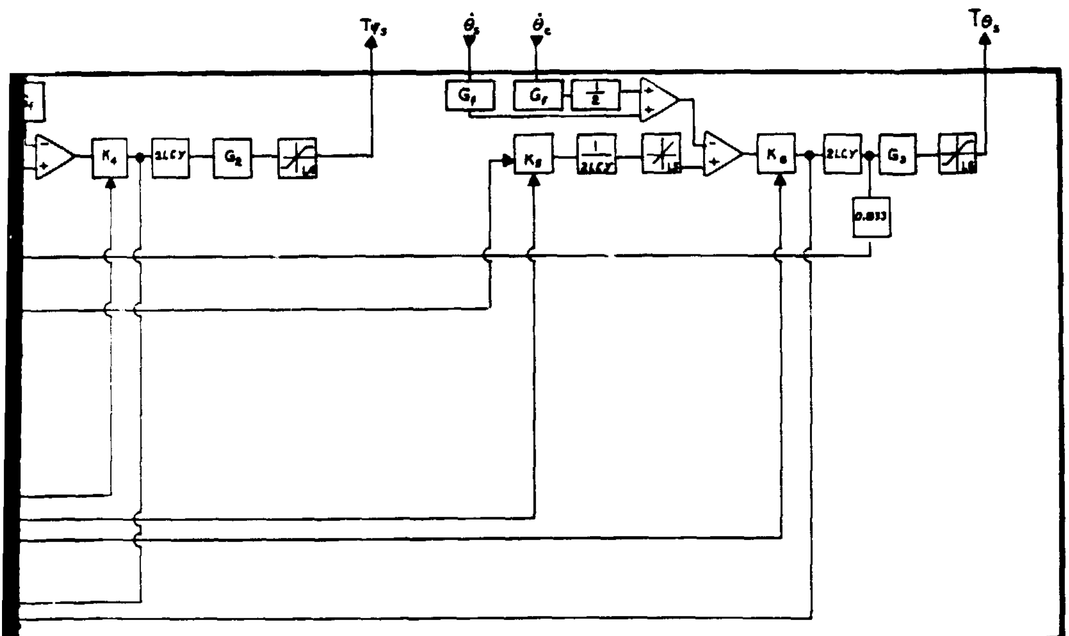
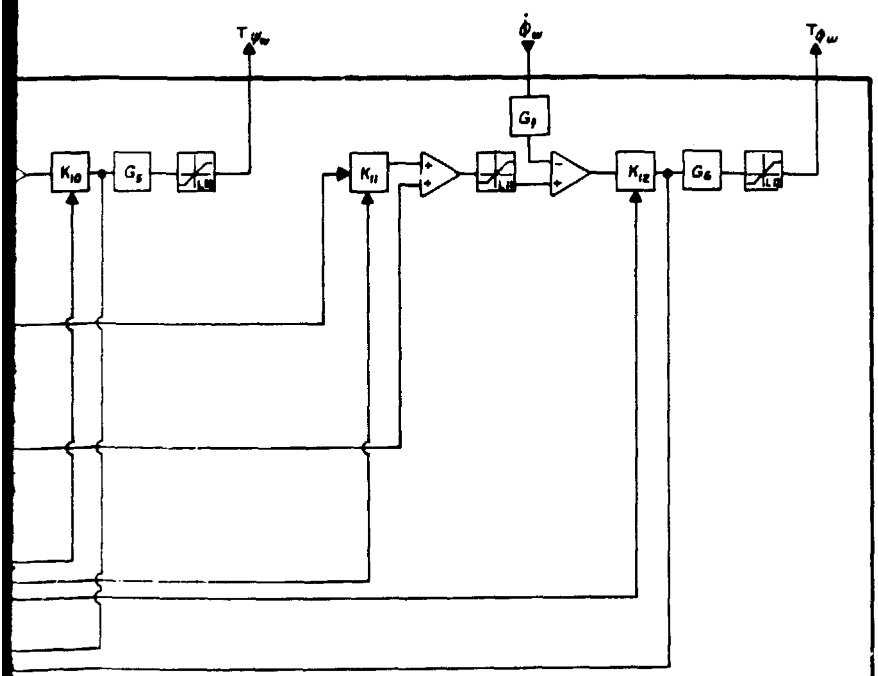


Figure VII-13 RAE/Rotation Control System

FOLDOUT FRAME 1



L LAWS AND SERVO SYSTEM (TRANSLATION)



OL LAWS AND SERVO SYSTEM (ROTATION)

Notation

1. $\dot{\psi}_s$, $\dot{\theta}_s$, $\dot{\theta}_e$, $\dot{\theta}_w$, $\dot{\psi}_w$, $\dot{\phi}_w$ = actual gimbal rate

2. $T\psi_s$, $T\theta_s$, $T\theta_e$, $T\theta_w$, $T\psi_w$, $T\phi_w$ = commanded gimbal torques

3. $\dot{R}$, $\dot{A}$, $\dot{E}$ = Range, Azimuth, & Elevation Commands

4. $\dot{\underline{X}}_c$ = X, Y, and Z commands given in terminal device axis

5.
$$T = \begin{bmatrix} C(\theta_w+\gamma)C\psi_w & -C(\theta_w+\gamma)S\psi_w & S(\theta_w+\gamma) \\ S\psi_w & C\psi_w & 0 \\ -S(\theta_w+\gamma)C\psi_w & S(\theta_w+\gamma)S\psi_w & C(\theta_w+\gamma) \end{bmatrix}$$

Terminal device to range vector transformation

6. $\gamma = 1/2\ \theta_e$

7. L = Lower arm segment length

8. $\dot{\theta}_{wc}$, $\dot{\psi}_{wc}$, $\dot{\phi}_{wc}$ = commanded wrist attitude rates

9.
$$\dot{\theta}_{wh} = -\dot{\theta}_e - \dot{\theta}_s - T\psi_w S\theta_1 \dot{\psi}_s$$
$$\dot{\psi}_{wh} = -C\theta_1 \dot{\psi}_s$$
$$\dot{\phi}_{wh} = \frac{S\theta_1 \dot{\psi}_s}{C\psi_w}, \text{ where } \theta_1 = \theta_e + \theta_s + \theta_w$$

wrist attitude Hawk commands

10. K_i, i = odd = variable controller sensitivity gain

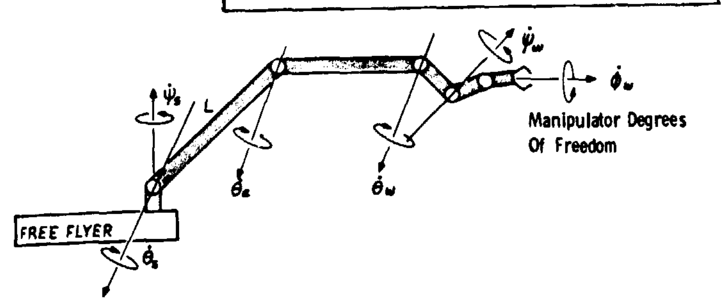
11. K_i, i = even = variable gimbal forward loop gain

12. L_i, i = odd = computed gimbal rate limit

13. L_i, i = even = computed gimbal torque limit

14. G_i, servo compensation network

15. G_f, tachometer ripple filter



Noted from the figure, both the Hawk mode and T matrix inclusion are operator selectable from the control console. The limiters L_i, i = odd, control the magnitude of the derived gimbal rate commands and thus prevent the joint rates from exceeding designed values as the manipulator is extended to the extremes of its operating volume. To prevent permanent magnet demagnetization and commutation arcing resulting from excessive motor currents, limiters L_i, i = even, are provided to control the torque commands derived from large error signals. These limiters, in conjunction with current limiting on the drive power amplifiers, fully protect the dc torquers from exceeding any design parameter.

The variable gains K_1, K_3, and K_5 determine the translational controller sensitivity and are operator variable (Fig. VII-14, control 1) from 0 - 2 ft/sec.

Likewise K_7, K_9, and K_{11} set the rotational controller sensitivity and are varied from 0 - 10°/sec (control 2). Gains K_2, K_4, and K_6 vary the translational motion servo stiffness (control 3) and are adjustable from the maximum value to zero-allowing the shoulder yaw, pitch and elbow pitch gimbals to freely backdrive. Rotational servo stiffness is set by control 4 and is similarly variable from maximum to zero-permitting the wrist attitudes to easily backdrive and selfalign. Filters G_f and G_i, $i = 1 \ldots 6$, detailed below, are the tachometer ripple filters and servo compensating n orks, respectively.

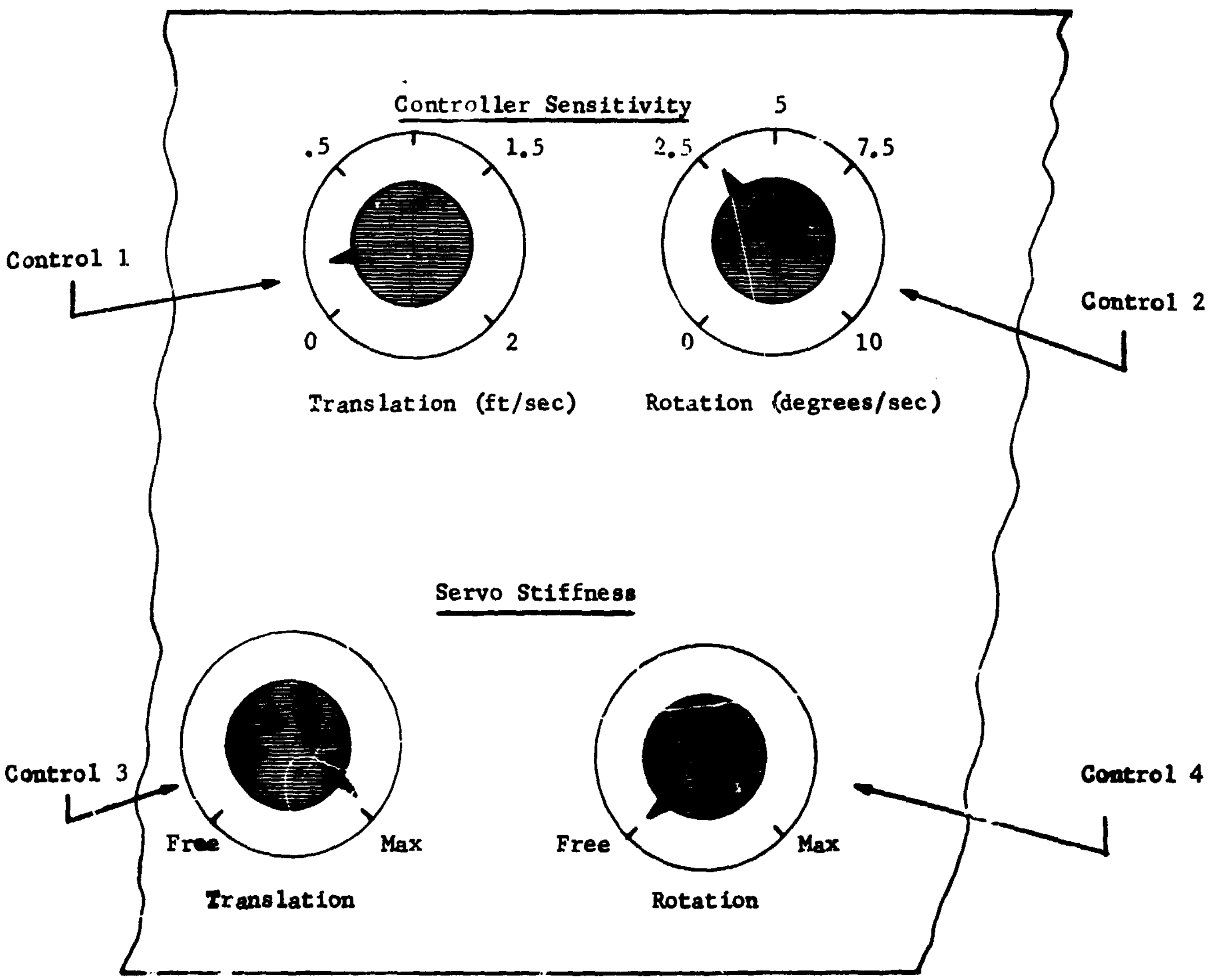


Figure VII-14 Partial Control Console

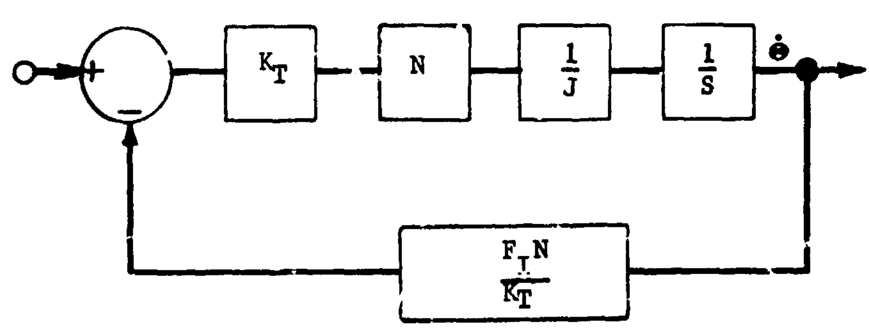
2. Servo Compensation Networks

Each servo loop must be compensated such that adequate stability is maintained over the full range of K_i, i = even, gain and inertia changes. The joint inertias will vary from the unloaded arm values to the increased reflected inertias corresponding to the fully loaded situation (300 lbs payload attached to terminal device). Compensation network design is achieved by:

1. deriving the open loop transfer function for all loop associated with each gimbal actuator,
2. linearizing each transfer function about a nominal arm configuration,
3. determine open loop servo characteristics via standard Bode analysis,
4. derive needed compensation network to assure stability and yield a three hz bandwidth for unloaded operation.

Since the control law equations compute actuator torques, a current drive technique is utilized to provide a speed independent command to activate the joint motors.

a. Shoulder Yaw - The generalized servo model used for the six joint actuator motor-gear assemblies is depicted in Fig. VII-15.



K_T = torque sensitivity
N = gear ratio
J = motor, gear, and load inertia
S = Laplace operator
F_I = infinite impedence damping coefficient
$\dot{\theta}$ = gimbal rate

Figure VII-15 Motor and Gear Train Servo Model

The closed loop transfer function associated with this model is given by:

$$G_m = \frac{\frac{K_T}{F_I N}}{1 + \frac{S}{F_I N^2/J}} \cdot \qquad \text{(VII-1)}$$

The servo loop associated with the shoulder yaw degree of freedom is determined from the azimuth control equations (Fig. VII-13) as shown in Fig. VII-16 .

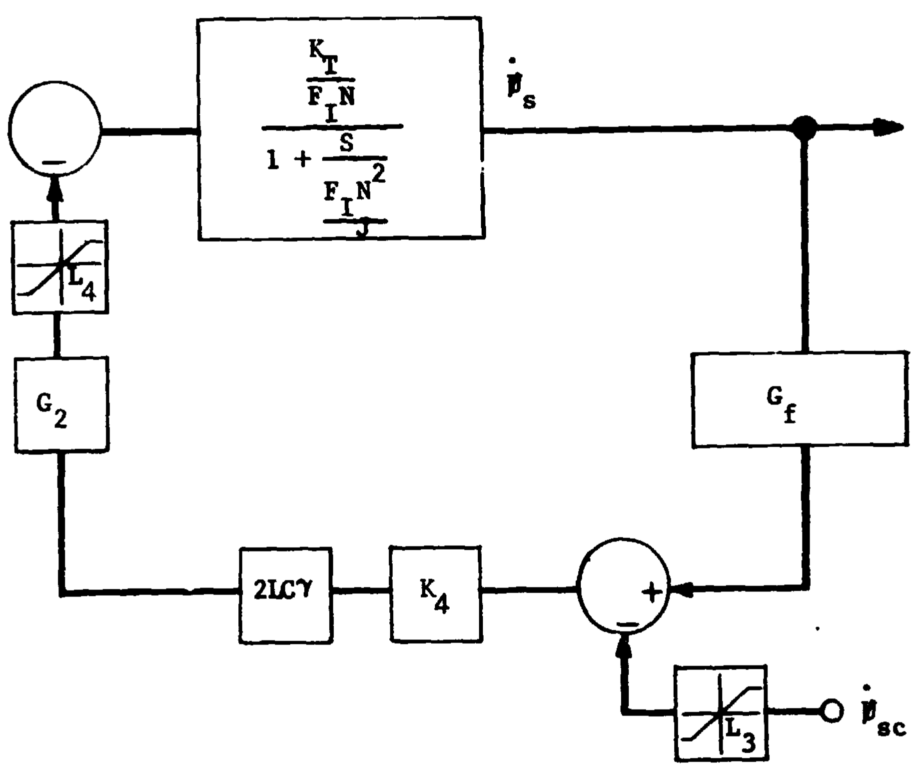


Figure VII-16 Shoulder Yaw Servo Loop

The limiters L_3 and L_4 are set to limit at 0.2 rad/sec and 90 ft lbs, respectively. The tachometer ripple filter, of the low pass variety with a break frequency of 30 hz, has a transfer function given by:

C-3

$$G_f = \frac{1}{1 + \frac{S}{188}}. \qquad \text{(VII-2)}$$

The motor parameters for the Inland T-4427 and the designed gear ratio are:

$$K_T = 0.43 \text{ ft lbs/amp} \qquad \text{(VII-3)}$$
$$F_I = 0.005 \text{ ft lbs/rad/sec}$$
$$N = 50:1.$$

Linearizing about a nominal arm configuration and estimating the no load reflected inertia yields:

$$2LC\gamma = 5.89 \text{ ft} \qquad \text{(VII-4)}$$
$$J = 15.42 \text{ ft lbs sec}^2$$

From the SMA simulation and previous manipulator experience, a static servo compliance of 15×10^3 ft lbs/rad/sec for the shoulder gimbals appears more than adequate to yield satisfactory rate resolution and servo stiffness. Assuming a unity gain current drive power amplifier, the forward loop gain K_4 is solved to be:

$$K_4 = \frac{15 \times 10^3}{(N)(K_T)(2LC\gamma)} = 118. \qquad \text{(VII-5)}$$

Substituting the above values into the servo loop of Fig. VII-16, the open loop transfer function for the shoulder yaw degree of freedom becomes:

$$G_{OL} = \left(\frac{1200}{1 + \frac{S}{0.81}}\right)\left(\frac{1}{1 + \frac{S}{188}}\right) G_2 . \qquad \text{(VII-6)}$$

Plotting the Bode gain curve of $\frac{G_{OL}}{G_2}$ (Fig. VII-17) reveals the filter network

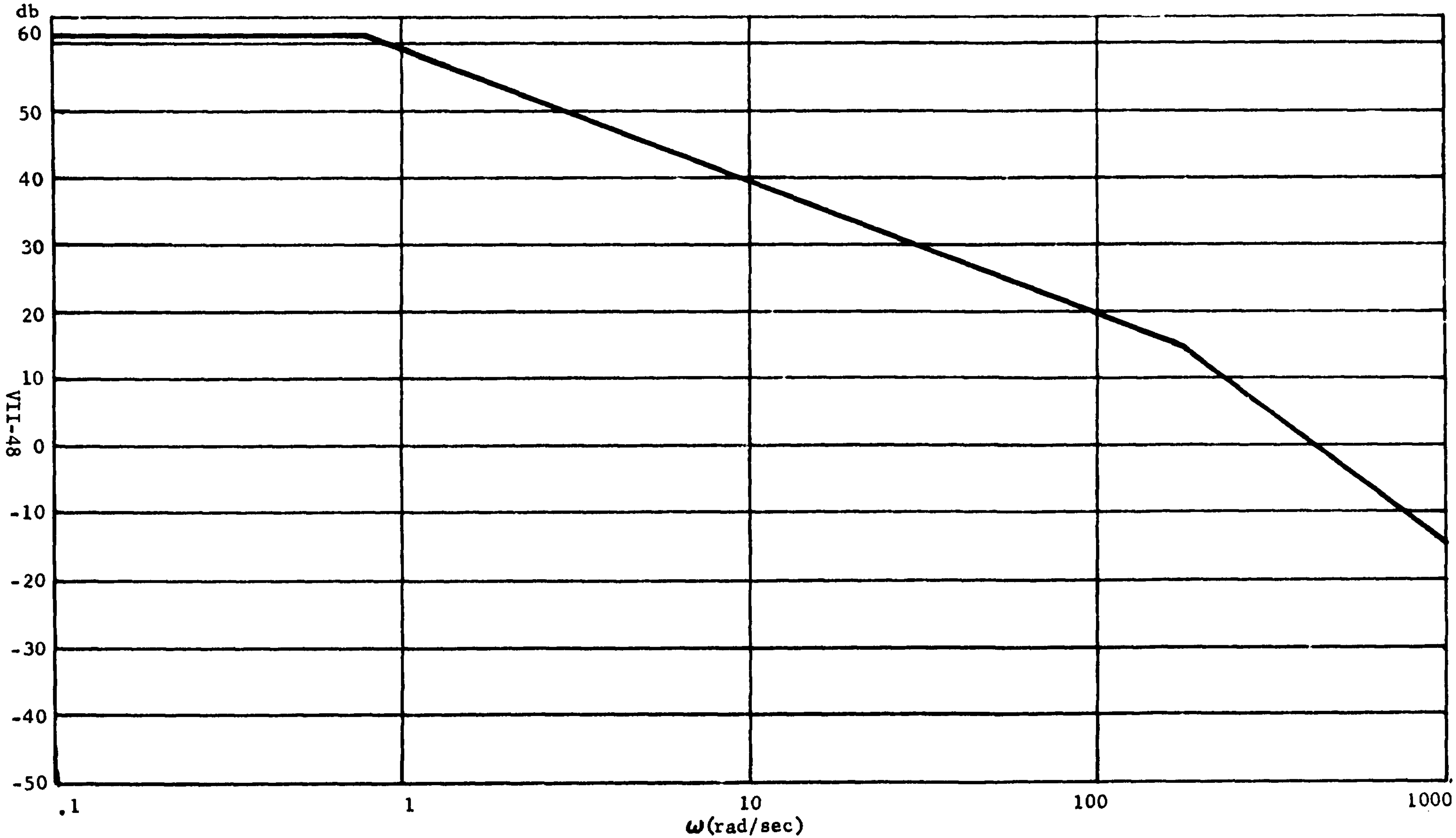


Figure VII-17 Bode Gain of Uncompensated Shoulder Yaw Servo Loop

$$G_2 = \frac{(1 + \frac{S}{.5})(1 + \frac{S}{20})}{(1 + \frac{S}{.1})(1 + \frac{S}{4})} \qquad \text{(VII-7)}$$

yields a compensated system (Fig. VII-18) with an unloaded bandwidth of approximately 5.25 hz and a phase stability margin always equal to or greater than 47° as the servo compliance varies from 15 x 10^3 ft lbs/rad/sec to 0 and as the load inertia reflected to the yaw gimbal ranges between 15.42 ft lbs sec^2 (unloaded) to 774 ft lbs sec^2 (300 lbs payload attached).

b. Shoulder Pitch - The shoulder pitch servo loop (Fig. VII-19), defined by the elevation degree of freedom control equations (Fig. VII-13), has the following open loop transfer function:

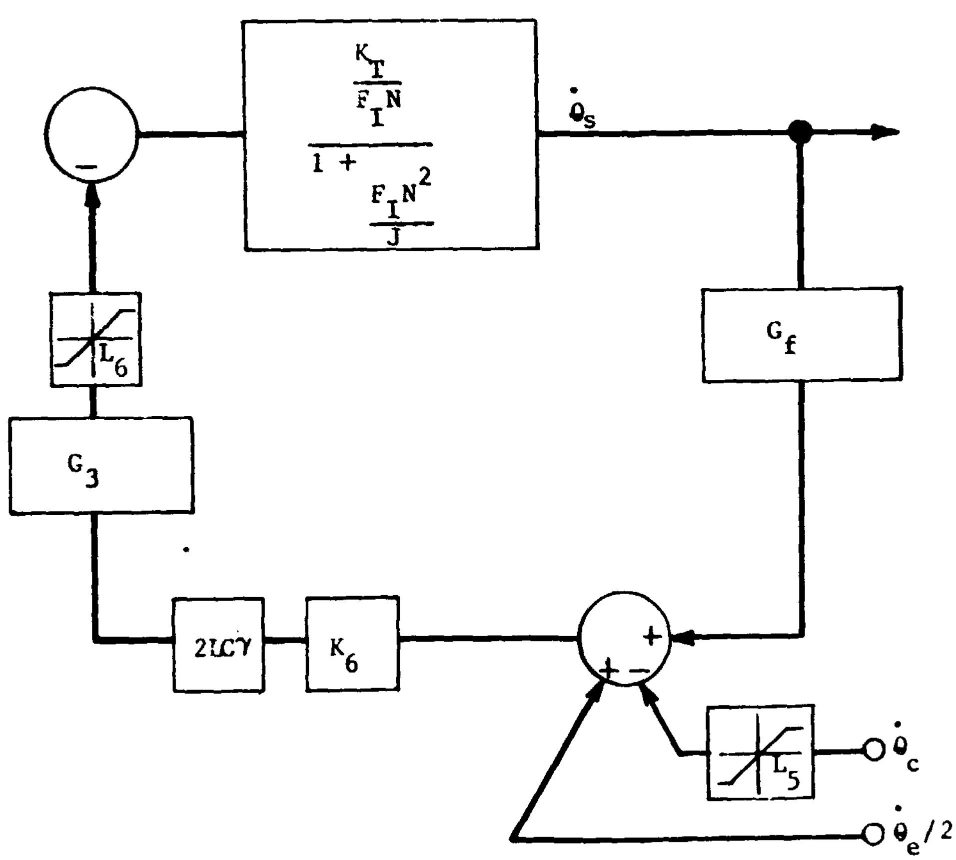


Figure VII-19 Shoulder Pitch Servo Loop

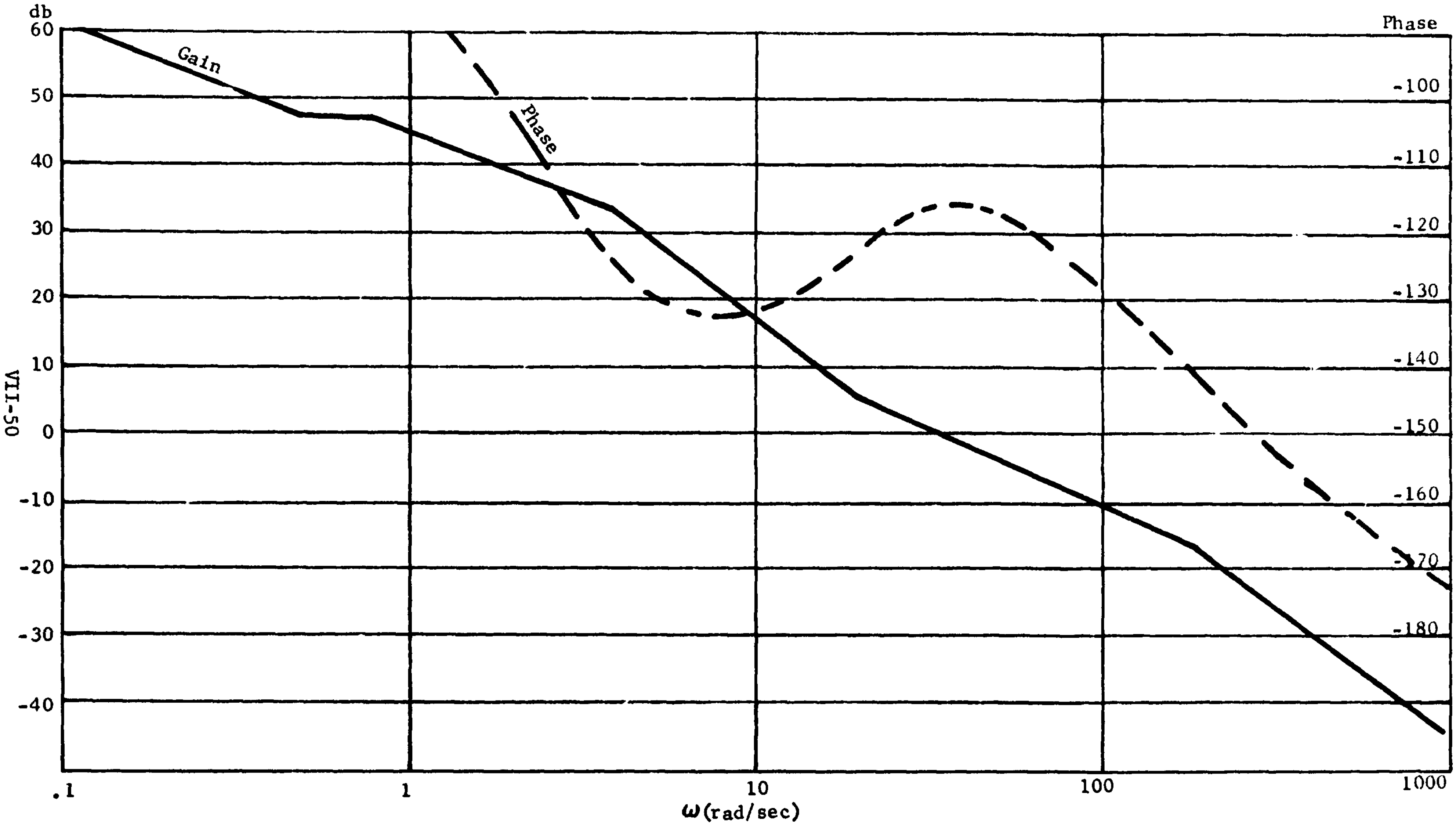


Figure VII-18 Compensated Shoulder Yaw Servo Loop

$$G_{OL} = (K_6)(2LC\ )\left(\frac{\frac{K_T}{F_I N}}{1 + \frac{S}{F_I N^2/J}}\right)\left(G_f\right)\ \left(G_3\right)\ , \qquad \text{(VII-8)}$$

where

$L_5 = 0.2$ rad/sec

$L_6 = 90$ ft lbs

$K_T = 0.43$ ft lbs/amp

$N = 50:1$

$F_I = 0.005$ ft lbs/rad/sec

$2LC\gamma = 5.89$ ft (nominal configuration)

$K_6 = 118$ (corresponding to a 15×10^3 ft lbs/rad/sec servo compliance)

$J = 23.08$ ft lbs sec^2 (unloaded manipulator)

$G_f = \frac{1}{1 + \frac{S}{188}}$.

Performing the above substitutions, equation (VII-8) becomes

$$G_{OL} = \left(\frac{1200}{1 + \frac{S}{0.54}}\right)\left(\frac{1}{1 + \frac{S}{188}}\right) G_3\ . \qquad \text{(VII-9)}$$

A Bode gain plot of $\frac{G_{OL}}{G_3}$ reveals the compensation network

$$G_3 = \frac{(1 + \frac{S}{.5})(1 + \frac{S}{20})}{(1 + \frac{S}{.1})(1 + \frac{S}{5})} \qquad \text{(VII-10)}$$

yields an unloaded bandwidth of 4.77 hz and provides a phase margin $\geq 47°$ for all mode of operation.

c. Elbow Pitch - The range and elevation control equations appear in the elbow servo loop as shown by Fig. VII-20.

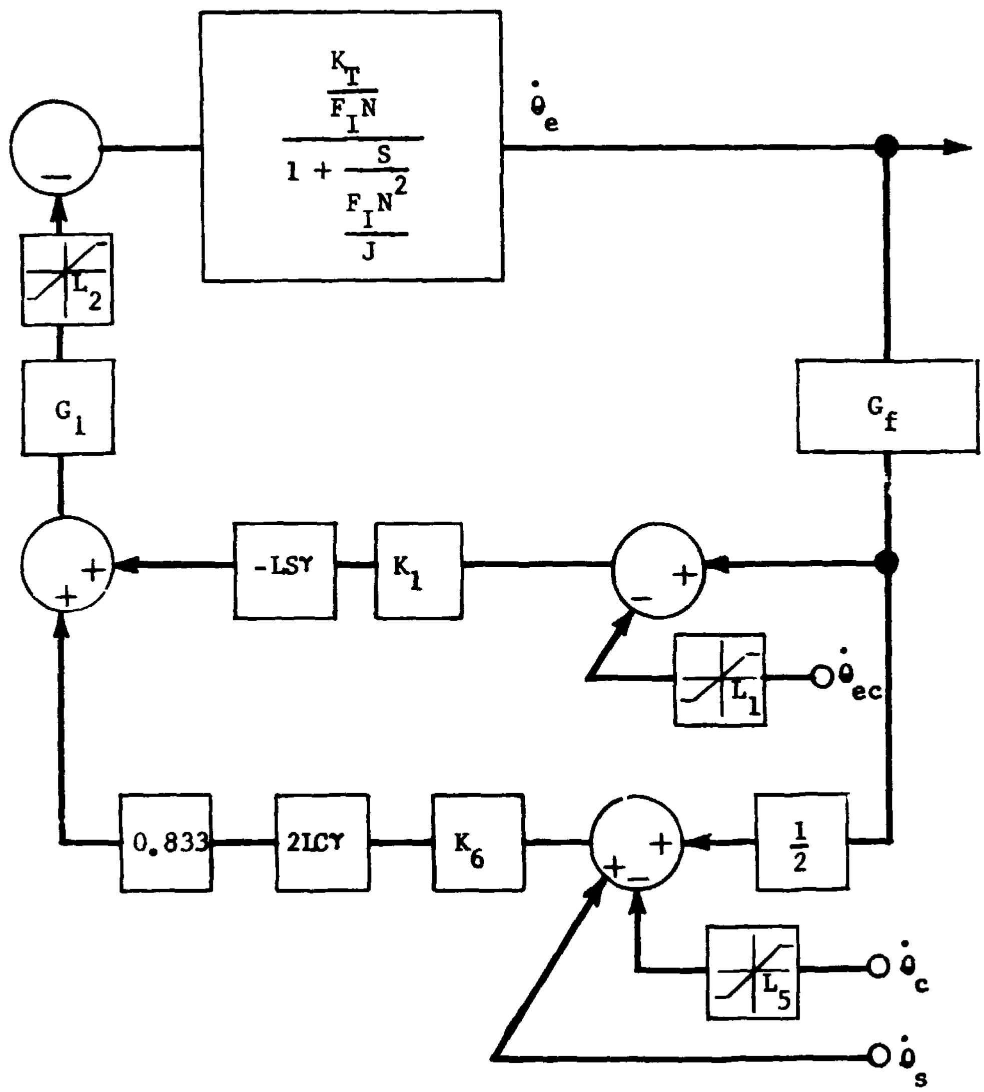


Figure VII-20 Elbow Pitch Servo Loop

Performing the substitutions:

L_1 = 0.2 rad/sec
L_2 = 49 ft lbs
K_T = 0.43 ft lbs/amp
F_I = 0.005 ft lbs/rad/sec
N = 30:1

$-LS\gamma = 2.95$ ft

$2LC\gamma = 5.89$ ft

$K_1 = 210$ (corresponding to an 8×10^3 ft lbs/rad/sec servo compliance)

$K_6 = 118$

$J = 9.98$ ft lbs $\sec^2$ (unload)

the open loop transfer function is

$$G_{OL} = \left(\frac{2609}{1 + \frac{S}{0.45}}\right)\left(\frac{1}{1 + \frac{S}{188}}\right) G_1 \, . \qquad \text{(VII-11)}$$

The plot of $\frac{G_{OL}}{G_1}$ reveals the compensator

$$G_1 = \frac{(1 + \frac{S}{.7})(1 + \frac{S}{30})}{(1 + \frac{S}{.1})(1 + \quad + \frac{S}{5})} \qquad \text{(VII-12)}$$

provides an unloaded bandwidth of 5.25 hz and a phase margin $\geq 43^\circ$ for all facets of control.

d. <u>Wrist Pitch</u> - Fig. (VII-21) depicts the wrist pitch servo loop

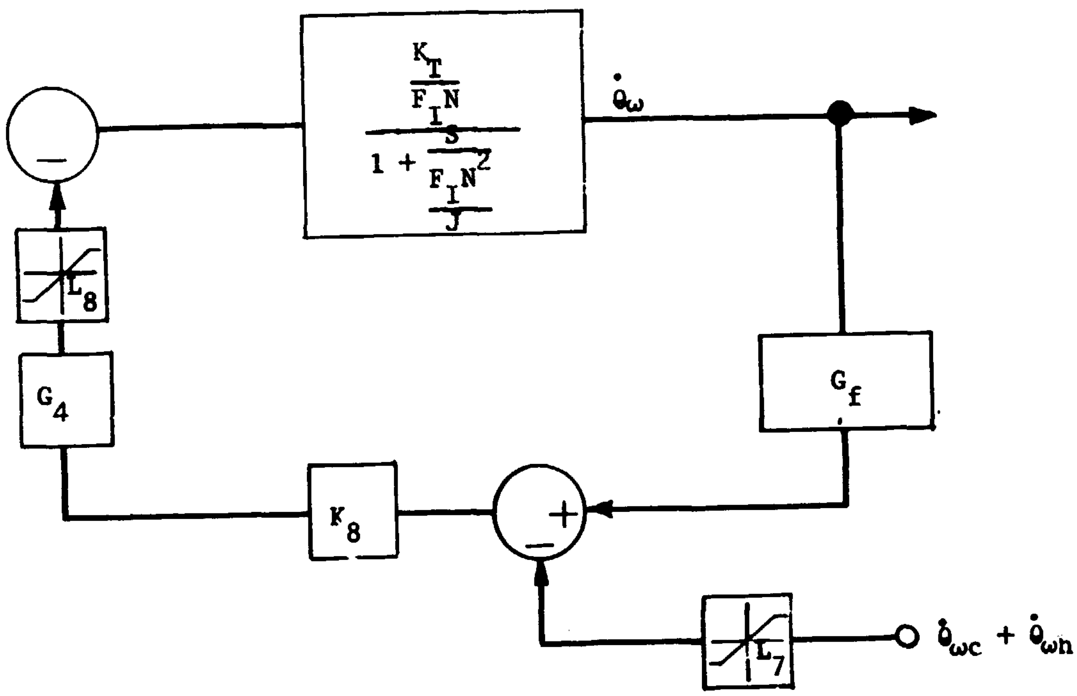


Figure VII-21 Wrist Pitch Servo Loop

With the substitutions

K_T = 0.21 ft lbs/amp (Magtech 3000B-78)
N = 42.6:1
F_I = 0.0004 ft lbs/rad/sec
L_7 = 0.2 rad/sec
L_8 = 15 ft lbs
K_8 = 223 (2×10^3 ft lbs/rad/sec servo compliance)
J = 0.47 ft lbs sec^2 (unloaded)

the open loop transfer function becomes

$$G_{OL} = \left(\frac{2754}{1 + \frac{S}{1.54}}\right)\left(\frac{1}{1 + \frac{S}{188}}\right) G_4. \qquad \text{(VII-13)}$$

The filter network

$$G_4 = \frac{(1 + \frac{S}{.6})(1 + \frac{S}{25})}{(1 + \frac{S}{.1})(1 + \frac{S}{5})} \qquad \text{(VII-14)}$$

modifies G_{OL} such that the closed loop unloaded bandwidth is approximately 25 hz and a 45° or greater phase margin is maintained.

e. Wrist Yaw - Fig. VII-22 represents the wrist yaw servo loop.

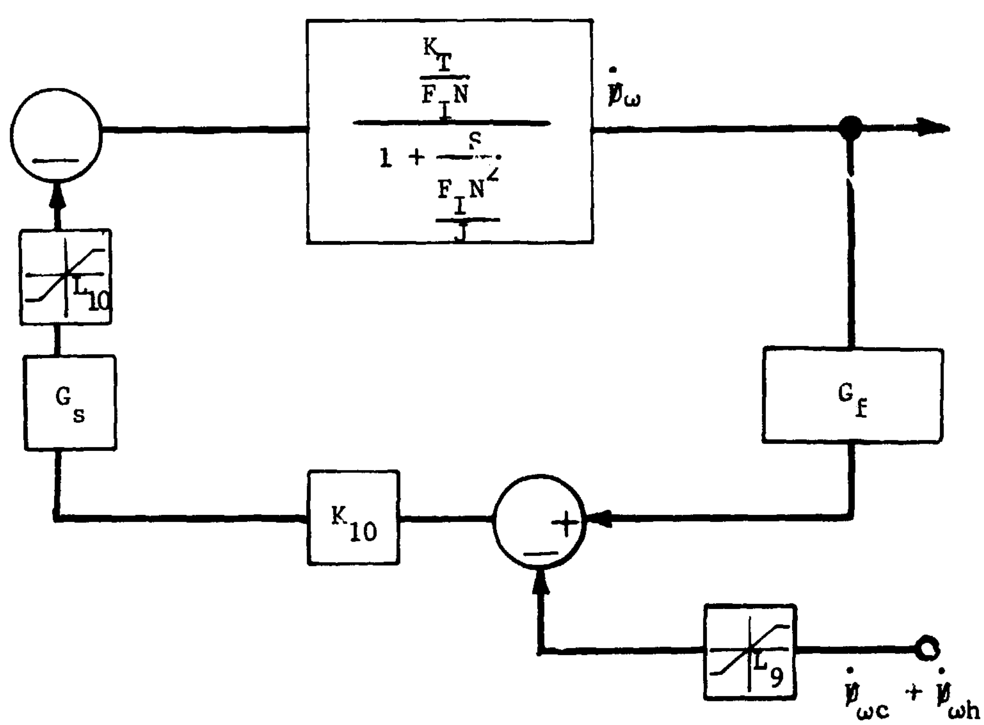


Figure VII-22 Wrist Yaw Servo Loop

The loop parameters

$L_9 = 0.2$ rad/sec

$L_{10} = 15$ ft lbs

$K_T = 0.21$ ft lbs/amp

$F_I = 0.0004$ ft lbs/rad/sec

$J = 0.29$ ft lbs sec^2 (unloaded)

$N = 42.6:1$

$K_{10} = 223$ (2×10^3 ft lbs/rad/sec servo compliance)

yield the open loo" transfer function

$$G_{OL} = \left(\frac{2754}{1 + \frac{S}{2.5}}\right)\left(\frac{1}{1 + \frac{S}{188}}\right) G_5. \qquad \text{(VII-15)}$$

Inserting

$$G_5 = \frac{(1 + \frac{S}{.8})(1 + \frac{S}{30})}{(1 + \frac{S}{.1})(1 + \frac{S}{5})} \qquad \text{(VII-16)}$$

compensates the loop to yield a 24 hz unloaded bandwidtn and a phase margin $\doteq 40°$.

f. Wrist Roll - The wrist roll servo loop is depicted in Fig. VII-23

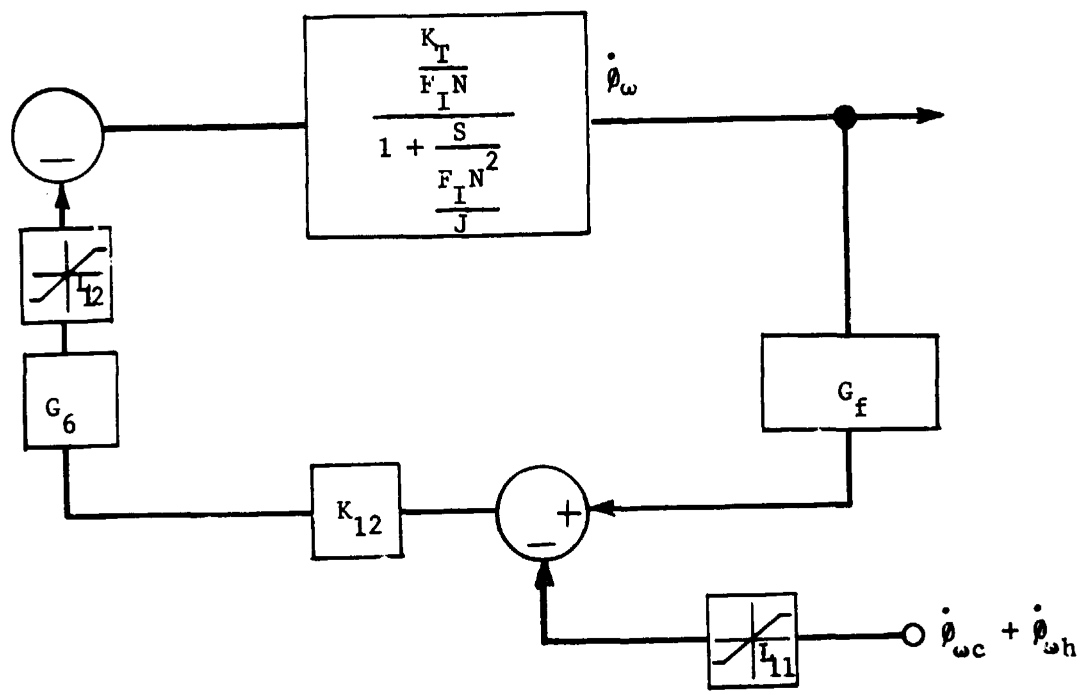


Figure VII-23 Wrist Roll Servo Loop

Defining the above variables:

L_{11} = 0.2 rad/sec

L_{12} = 15 ft lbs

K_T = 0.21 ft lbs/amp

F_I = 0.0004 ft lbs/rad/sec

J = 0.21 ft lbs sec^2

N = 42.6:1

K_{12} = 223 (2 x 10^3 ft lbs/rad/sec servo compliance)

the open loop transfer function

$$G_{OL} = \left(\frac{2754}{1 + \frac{S}{3.46}}\right)\left(\frac{1}{1 + \frac{S}{188}}\right) G_6, \qquad \text{(VII-17)}$$

associated with the compensator

$$G_6 = \frac{(1 + S)(1 + S/30)}{(1 + \frac{S}{.1})(1 + \frac{S}{5})} \qquad \text{(VII-18)}$$

provides a 24 hz unloaded closed loop bandwidth and a phase margin $\geqq 35°$.

g. <u>Terminal Device Jaws</u> - The terminal device jaw assembly contains a servo actuator but no position or rate sensor. Jaw closure and opening will be accomplished by supplying an on-off polarized command to the motor drive electronics. Variable jaw speed is achieved by using a "bump" technique on the command switch.

C. DATA MANAGEMENT

The following paragraphs discuss the data management for the manipulator arm applicable to a free flying teleoperator. A comparison of telemetry bandwidth for both a complicated arm and a simpler arm are shown. Briefly, it is concluded that when a rate control mode is employed a command bandwidth of approximately 1 kHz and a telemetry bandwidth of less than 2 kHz is sufficient. In this mode of operation, arm angular position data is used for display purposes only and test and verification sequences are accomplished in conjunction with the television and direct analysis of telemetry signals.

1. Overall Data Management Considerations

A basic diagram relating a manipulator of typical component complement to a remotely located man/machine interface is shown in Fig. VII-24. The elements located on the Free Flyer include manipulator actuator and sensors, telemetry signal conditioning for relay, command reception and conditioning for the manipulator servo actuators. The characteristics of the television module and possible separate video transmitter link have been addressed in previous work such as contract NAS8-29024, "Conceptual Design Study of a Teleoperator Visual System".

The man/machine interface consists of television displays, auxiliary visual displays, potential audio and contact cues, and the physical input devices for the manipulator and television control. Manipulator input devices are conditioned from controller coordinates to manipulator actuator coordinates by a control mode computation unit. The control computation unit is required to provide a set of control laws and modes including the range/azimuth/elevation "rate-rate" and "hawk" mode in spherical or cartesian coordinates. Control select logic provides a capability for selection of potential direct or backup control of the manipulator in the case of a failure or contingency.

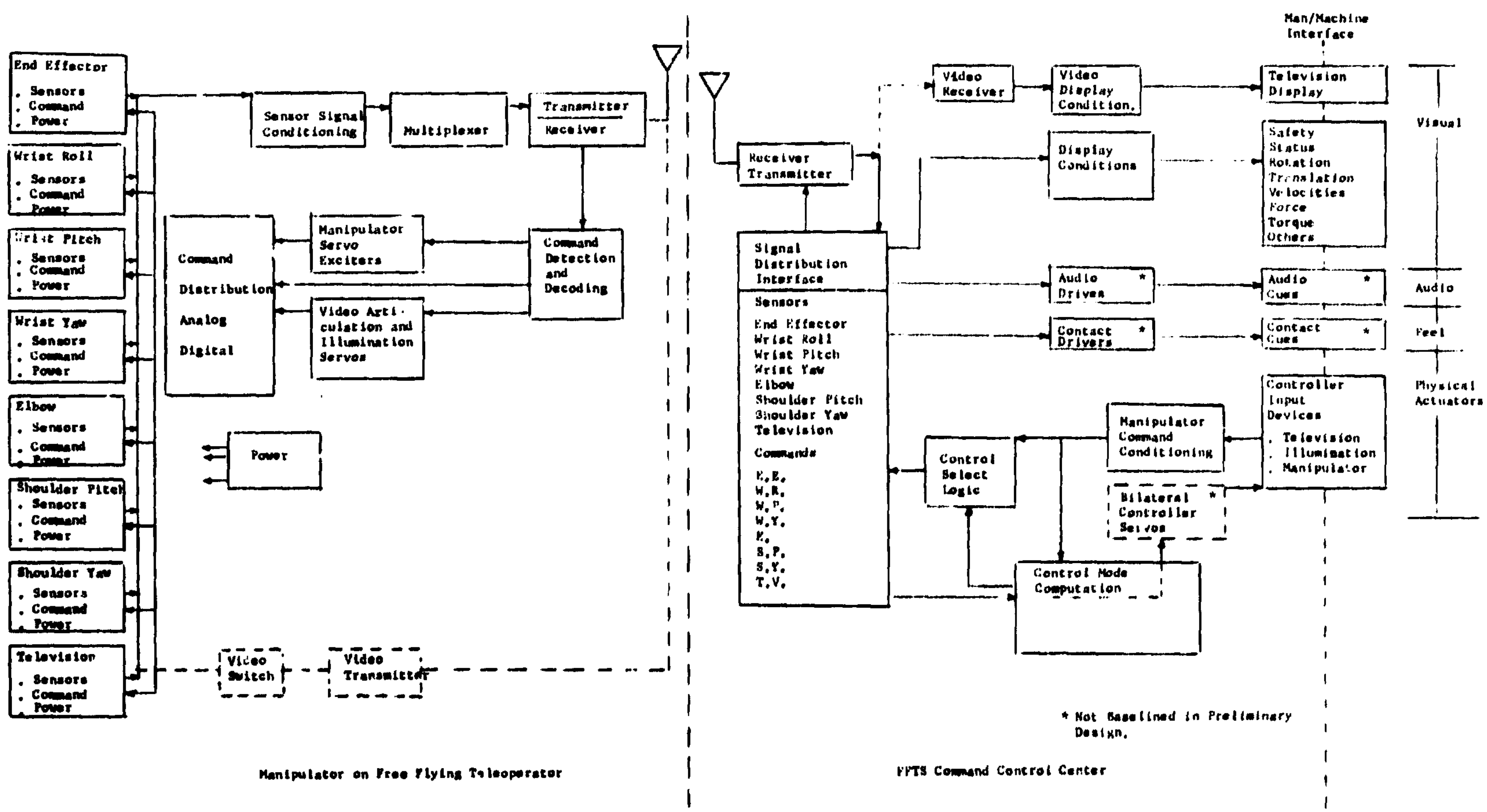


Figure VII-24 Major Manipulator Data Sources and Interrelationships

With respect to telemetry, or data management, for a manipulator the design characteristics of signals which lead to a determination of channel bandwidths are basically: Type (analog or discrete); dynamic range (ratio of maximum to minimum value); and sample rate or bandwidth.

In this case the parameters of interest are: a) Motor torque; b) motor or shaft velocity; and c) angular position of a shaft.

a. Motor Torque Sampling - Motor torque on a shaft results in an applied force at the end of the shaft. Control laws have been defined which could either employ the motor torque directly, or compute it based on a value of applied tip force. The factor of primary interest to telemetry is the relationship of threshold torque to maximum torque. The threshold torque is primarily the breakaway torque due to motor stiction. This factor tends to be relatively constant for a given motor, and is on the order of 2% of maximum torque for the devices anticipated for application to a typical FFTS manipulator. Thus a preliminary allocation of sampling threshold of 1% of maximum torque appears sufficiently conservative.

The telemetry signal definition table therefore includes an allocation of 1% of maximum motor/gear train torque as a reasonable value. The remaining major consideration is sampling rate required. Specification of this value is usually made to follow the typical time interval for a degree of freedom to traverse a fixed percent of maximum angular travel under maximum angular acceleration expected.

An estimate of typical maximum angular acceleration can be based on the inertia of an unloaded manipulator about a shoulder joint and the applied torque about that joint.

Accordingly,

$$T = I\,\alpha \text{ and}$$

$$\alpha = T/I = \frac{90 \text{ ft-lb}}{39.05 \text{ slug-ft}^2} = 2.3 \text{ rad/sec}^2$$

where:

T = torque applied

α = angular acceleration

I = Inertia about the axis of rotation

In addition, a time interval can be incorporated by the equation:

$$\theta = \theta_o + \frac{1}{2}\alpha t^2$$

where:

θ, θ_o: angular positions

α: angular acceleration

t: time

In this case let $(\theta - \theta_o)$ be $\Delta\theta$, a portion of maximum angular travel for the particular joint. The portion of maximum travel allocated is 1% for an initial reference.

The time interval is given by:

$$t = \left(\frac{2 \cdot \Delta\theta}{\alpha}\right)^{1/2}$$

where the parameters were defined above. Table VII-8 summarizes the resultant sampling interval.

It is seen that an allocation of <u>10</u> samples/second will encompass all time increments derived.

Table VII-8 Time Increments to Traverse 1% of Maximum Angular Travel

	θ (deg)	θ (rad)	$.01\Delta\theta$	t (sec)	f (Hz)
Wrist Roll	360	6.28	.0628	.233	4.29
Wrist Pitch	180	3.14	.0314	.165	6.06
Wrist Yaw	170	2.96	.0296	.160	6.25
Elbow Pitch	180	3.14	.0314	.165	6.06
Shoulder Pitch	180	3.14	.0314	.165	6.06
Shoulder Yaw	400	6.98	.0698	.247	4.05

b. Tachometer or Angular Rate Sampling Considerations - Angular rate is used by the candidate control laws to provide rate damping (for stability), rate limiting for safety reasons, and for possible rate matching in some specialized applications.

The allocation of a rate precision may be, therefore, somewhat arbitrary. However, previous studies (NAS8-29904, and others) have defined typical rate residuals on the order of $\pm$ .1 deg/sec ($\pm$ 6 min/sec). This is also defined as a representative value by others in such analyses as NASW-2220 "Teleoperator System Man-Machine Interface Requirements for Satellite Retrieval and Servicing".

For a precision operation such as module replacement the tightest "limit cycle" might be bounded by $\pm$ .1 degree and $\pm$ 1.0 degree/second. This is taken as an initial allocation for a sampling requirement determination. In this case the time required to traverse the rate bound is:

$$\frac{.1 \text{ degree}}{1 \text{ degree/sec}} = .1 \text{ sec.}$$

Accordingly, a somewhat arbitrary assignment of a minimum sampling rate is $(.1)^{-1} = 10$ samples/second.

The implication of this approach is that rate is sampled at a sufficient rate to assure a tight rate bound while maintaining an acceptable precision on rate during slew maneuvers to maintain adequate loop damping. At higher angular rates the parameter of interest becomes the maximum angular increment possible between sampling intervals. These intervals are summarized in Table VII-9.

Table VII-9 Maximum Angular Increment Due to Tachometer Sampling Interval

	ω Max (deg/sec)	ω Max (rad/sec)	t (sample)* (sec)	θ (deg)	θ (rad)	% Max
Wrist Roll	± 120	± 2.1	.1	12	.21	10
Wrist Pitch	$\pm$ 10	$\pm$ .175	.1	1	.0175	10
Wrist Yaw	$\pm$ 10	$\pm$ .175	.1	1	.0175	10
Elbow Pitch	$\pm$ 20	$\pm$ .35	.1	2	.035	10
Shoulder Pitch	$\pm$ 10	$\pm$ .175	.1	1	.0175	10
Shoulder Yaw	$\pm$ 10	$\pm$ .175	.1	1	.0175	10

* Limit cycle of .1 deg and 1 degree/second

The worst case angular excursions between sampling must be further evaluated based as the resultant motion of the end effector due to this uncertainty. For example, with an uncertainty of 1° (.0175 rad) the movement uncertainty at the tip (9 feet) would be:

$$.0175 \text{ rad } (9 \text{ feet}) = .157 \text{ feet}$$

This does not appear excessive since maximum slew rate would not be employed toward an attach point when the payload or manipulator were in the close proximity of the attach point. Thus a sampling rate of 10/second is allocated.

c. <u>Position Potentiometer Sampling Considerations</u> - Knowledge of shaft position is most critical at low angular rates when precision alignment operations would be anticipated. The angular position increment threshold has been stated to be 6 min or .1 degree as an upper bound. The recommended value, however, is $\pm$ 1 degree precision.

A direct comparison of position and velcoity based on maximum allowable joint rates and the desired angular precision results in a representative sampling time interval. This is summarized as:

Joint Rate Maximum (deg/sec)	Angular Precision (deg)	ΔT (sec)	f (hz)
10°/sec	.1	.01	100
20°/sec	.1	.005	200
120°/sec	.1	0.000825	1200

These sample frequencies appear very high based on the expected servo bandwidths of up to 1 hz. Therefore, additional analysis is required to bound these values relative to the use of control equations.

For example, a rationale could be assumed that would include the concept that: precision angular knowledge would be maintained up to a maximum rate of a percent of maximum velocity (i.e., a value of 0.2 x ω_{max}). Thus the sampling rates would be:

$$f^* = k \cdot f_o$$

where:

f^* = adjusted sampling rate
K = proportional constant
f_o = sample rate implied

If k were set to 0.2, the corresponding sample rates are:

Joint Rate Maximum (deg/sec)	Angular Precision (deg)	ΔT (sec)	f (hz)
10	0.1	.05	20
20	0.1	.025	40
120	0.1	.000415	240

(For a one degree precision the maximum sampling rate implied is 24 Hz.)

In addition, a further special consideration must be given the wrist roll rate of 120 deg/sec. This rate implies an excessive sample frequency to maintain a constant rationale for sample rate choice. Since the high angular rate is for applications such as bolt removal, payload spin up, etc., the 0.1 deg precision is probably not required except at angular rates on the same order as other joints. Thus an actual sampling frequency can be deduced based on maintaining precision up to about 2°/sec as a worst case. This simply means that at an angular rate of 120°/sec, a sampling frequency of 20/sec would maintain angular granularity of:

$$\frac{120°/\text{sec}}{20\ \text{sample/sec}} = 6\ \text{deg/sample}\ (.105\ \text{radian})$$

and at 20°/sec = 1 deg/sample (.017 radian).

Both the above appear fully adequate for control and display purposes.

Composite Telemetry Table

A composite telemetry sampling table based on a versatile reference configuration and the above rationale is shown in Table VII-10.

The initial allocations of the telemetry control table indicate that a manipulator information rate of 1830 bits per second for a preferred simpler manipulator system.

The table is presented in expanded form to show the potential telemetry inclusions in a more complex implementation.

A typical command matrix for a manipulator on a FFTS is shown in Table VII-11. These initial assignments of resolutions and sampling rates are compatible with the manipulator. Based on the preferred rate control modes a command bandwidth incorporating some degree of conservatism is approximately 1122 Hz.

Table VII-10 Typical Manipulator Telemetry Matrix

Signal Source	Scale Range	Units	Resolution	Bits Sample	Sample Second	Bit/Second Complex System	Bit/Second Simpler System
Synchronization	11 bit Barker Code		--	11	10	110	110
Parity Check	8 bits		--	8	10	80	80
End Effector							
EE Motor	-20 to +20	Ft-lb	.1	10	5	50	50
EE Open	Binary	Discrete	--	1	1	1	--
EE Close	Binary	Discrete	--	1	1	1	--
EE Force Limit	0-20 lb	Lb	.1	9	5	45	--
EE Status	Binary	Discrete	--	2	1	2	--
EE Test Mode	Binary	Discrete	--	2	1	2	--
Wrist Roll							
WR Motor Torque	-15 to +15	Ft-lb	.15	8	10	80	80
WR Tachometer	-120 to +120	Deg/sec	1.2	8	10	80	80
WR Pot	Cont. ±180°	Deg	1 (.1 deg)	8	10	(.1 deg) 144	80
WR Brake	Binary	Discrete	--	1	10	10	--
WR + Limit	N/A						
WR - Limit	N/A						
WR Status	8	Binary	--	3	1	3	--
WR Test Mode	8	Binary	--	3	1	3	--
Wrist Yaw							
WY Motor Torque	-10 to +10	Ft-lb	.1	8	10	80	80
WY Tachometer	-10 to +10	Deg/sec	.1	8	10	80	80
WY Pot	-80 to +80	Deg	1 (.1)		10	220 (.1)	80
WY Brake	Binary	Discrete	--	1	10	10	10
WY + Limit	Binary	Discrete	--	1	10	10	--
WY - Limit	Binary	Discrete	--	1	10	10	--
WY Status	8	Discrete	--	3	1	3	--
WY Test Mode	8	Discrete	--	3	1	3	--
Wrist Pitch							
WP Motor Torque	-15 to +15	Ft-lb	.15	8	10	80	80
WP Tachometer	-10 to +10	Deg/sec	.10	8	10	80	80
WP Pot	-90 to +90	Deg	1 (.1)	8	10	220	80
WP Brake	Binary	Discrete	--	1	10	10	10
WP + Limit	Binary	Discrete	--	1	10	10	--
WP - Limit	Binary	Discrete	--	1	10	10	--
WP Status	8	Discrete	--	3	1	3	--
WP Test Mode	8	Discrete	--	3	1	3	--
Elbow Pitch							
EP Motor Torque	-50 to +50	Ft-lb	.1	10	10	100	100
EP Tachometer	-20 to +20	Deg/sec	.1	5	10	90	90
EP Pot	0 to -180	Deg	1 (.1)	8	10	240	80
EP Brake	Binary	Discrete	--	1	10	10	10
EP + Limit	Binary	Discrete	--	1	10	10	--
EP - Limit	Binary	Discrete	--	1	10	10	--
EP Status	8	Discrete	--	3	1	3	--
EP Test Mode	8	Discrete	--	3	1	3	---
Shoulder Pitch							
SP Motor Torque	-90 to +90	Ft-lb	.1	11	10	110	110
SP Tachometer	-10 to +10	Deg/sec	.1	8	10	80	80
SP Pot	0 to +180	Deg	1 (.1)	8	10	120 (.1 deg)	80
SP Brake	Binary	Discrete	--	1	10	10	10
SP + Limit	Binary	Discrete	--	1	10	10	--
SP - Limit	Binary	Discrete	--	1	10	10	--
SP Status	8	Discrete	--	3	1	3	--
SP Test Mode	8	Discrete	--	3	1	3	--
Shoulder Yaw							
SY Motor Torque	-90 to +90	Ft-lb	.1	11	10	110	110
SY Tachometer	-10 to +10	Deg/sec	.1	8	10	80	80
SY Pot	-200 to +200	Deg	1 (.1)	9	10	120	90
SY Brake	Binary	Discrete	--	1	10	10	10
SY + Limit	Binary	Discrete	--	1	10	10	--
SY - Limit	Binary	Discrete	--	1	10	10	--
SY Status	8	Discrete	--	3	1	3	--
SY Test Mode	8	Discrete	--	3	1	3	--
Total Bit Rates for Complex and Simpler Systems						2611 Hz	1830 Hz

Table VII-11 Command Matrix (Typical)

	Scale Range	Units	Resolution	Bits	Sample Rate	B/Sec Channel	Total Bit/Sec
Synchronization				8	10	80	80
Source Code				6	10	60	60
Parity				10	10	100	100
Spare				8	10	80	80
Emergency Signal		4	-	2	20	80	80
Video Sensor Mode and Control		From Previous Work (NAS8-29024)					102
End Effector Control							
EE Motor Torque	-20 to +20	ft-lb	.1	10	10	100	100
Wrist Roll							
WR Motor Torque	+15 to -15	ft-lb	.15	8	10	80	80
Wrist Yaw							
WY Motor Torque	-10 to +10	ft-lb	.1	8	10	80	80
WY Test Mode	4	Binary	-	2	1	2	2
Elbow							
E Motor	-50 to +50	ft-lb	.1	10	10	100	100
E Brake	2	Binary	-	1	10	10	10
Shoulder Pitch							
SP Motor	-90 to +90	ft-lb	.1	11	10	110	110
SP Brake	2	Binary	-	1	10	10	10
Shoulder Yaw							
SY Motor	-90 to +90	ft-lb	.1	11	10	110	110
SY Brake	2	-	-	1	10	10	10
						Total	1122 Bit/Second

D. CONTROL AND DISPLAY STATION

The Control and Display Station (CDS) provides the man/machine interface necessary for the remote manned supervisory control of the FFTS. The prime objective of this Section is to provide a preliminary CDS concept configuration that integrates the manipulator control and display elements into a total integrated FFTS CDS. The CDS in question may be located in the Shuttle, a sortie laboratory, or on the ground. Each of these locations present different problems in establishing CDS requirements. For example, because of the potential weight and volume restrictions within the Shuttle and sortie lab, control station configuration and packaging concepts must stay within specified volume envelopes. However, the ground station volume configuration is primarily limited by the operator's physical capabilities and arthropometry considerations.

A review of the potential locations have indicated the Shuttle Orbiter location to be the most restrictive, as to volume, weight, and man/machine parameters. Therefore, this location was selected for further study.

In the CDS conceptual development, the man/machine interfaces associated with two different manipulator controllers were considered.

Fig. VII-25 presents the logic flow approach used in developing the specific interactions needed to layout an integrated FFTS CDS panels.

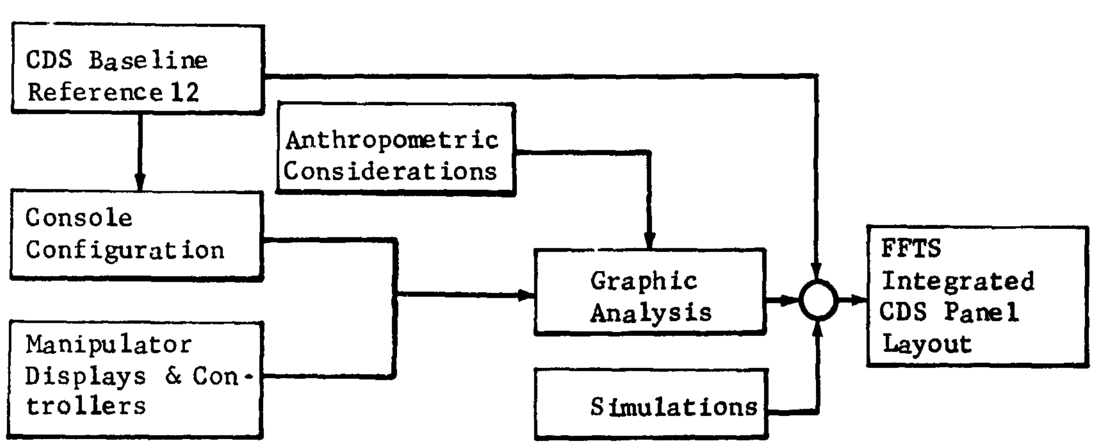


Figure VII-25 Integrated Control and Display Panel Layout Analysis Flow

1. FFTS CDS Baseline

The initial problem posed for this study was the selection of a representative control station configuration compatible with both the man/machine aspect as well as the integration aspects of manipulator control hardware. A review of completed and projected NASA studies showed considerable effort in progress to further refine the Shuttle located FFTS CDS. From a completed NASA study (Ref. 12) a panel configuration was baselined which presents a generalized FFTS control and display layout.

2. Control and Display Console Configuration

The Generalized CDS Console Configuration baselined was one which emphasized the man/machine interactions associated with defining a FFTS dedicated CDS. In summary the information reported in Reference 12 defines a single operator integrated control station where the human factors considered were viewing distance, functional reach, comfort and operator restraint locations. A systems optimization approach was utilized in outlining a compatible console envelope. Using this information the following configuration and guidelines have been assumed and baselined for this study:

- An indirect visual system using dual over-under monitors with stereo-mono displays was assumed.
- Operator head/eyes viewing position is defined as a point 22 inches distant along the normal line of sight, perpendicular to the center of the Fresnel display screen. The normal line of sight is the comfort line of sight which is 15 degrees below the horizontal line of sight.
- A control and display panel zonal classification was derived by the subtended angle approach for the 5th percentile operator visual and functional reach comfort range. Using this approach resulted in the panel depicted in Fig. VII-26. Growth to this

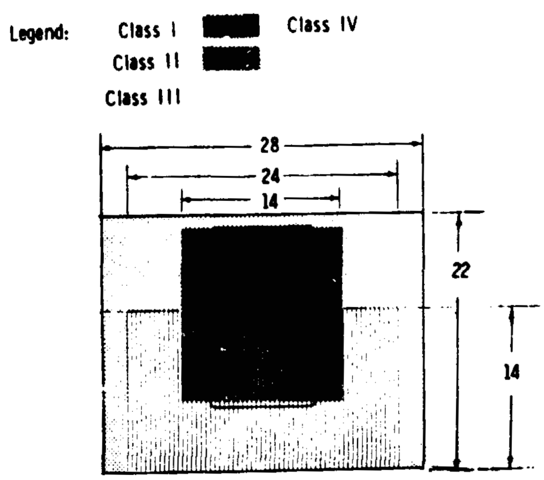


Figure VII-26 CDS Panel Zonal Classification

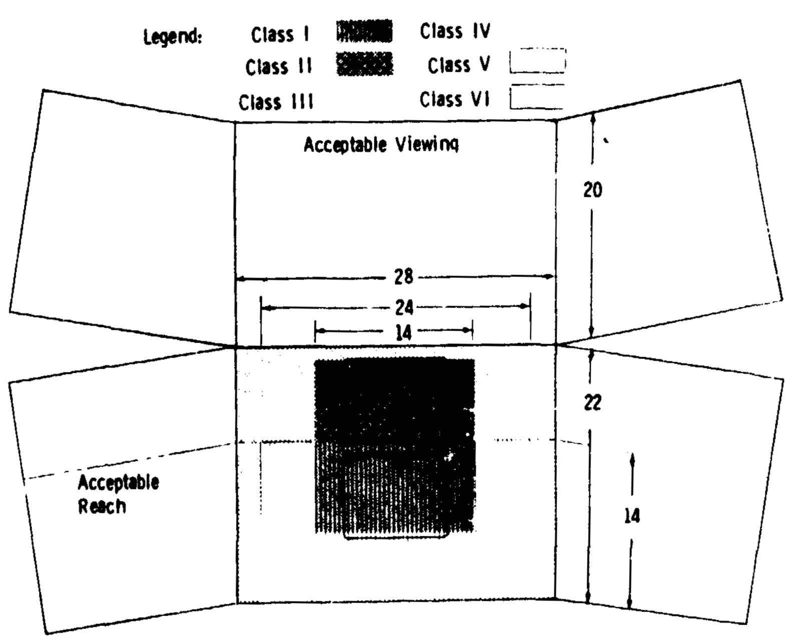


Figure VII-27 Growth Area for CDS Panel

concept is depicted in Fig. VII-27 which shows how modularized side panels would be added as required. Each zonal classification has the following general description:

Class I - Control and display elements requiring optimum viewing and reach locations;

Class II - Control and display elements requiring optimum viewing;

Class III - Control and display elements requiring optimum reach locations;

Class IV - Control and display elements requiring maximum viewing without rotating head;

Class V - Control and display elements requiring acceptable reach and viewing;

Class VI - Display elements requiring acceptable viewing only.

3. Manipulator Displays and Controls

The primary purpose of this analysis was to define the preliminary working volume available for manipulator controller concepts using the CDS baseline as defined in the preceding paragraphs.

The emphasis in deriving the available working envelope was directed at the man/machine interface compatibility. The primary interface was the FFTS operator location in relation to the control and display console hardware. This includes the basic integration of the FFTS control and display elements into a logical and optimum arrangement within a limited volume while incorporating human factor considerations necessary for the operator to perform effectively.

Two manipulator controllers were identified in Section IV-B as being feasible to provide adequate input commands.

The most common of these two control methods was the dual Apollo type units which were panel mounted and, had 3-degree-of-freedom for each rate hand controller. The second unit was a floor mounted 6-degree-of-freedom vertical sliding bilateral (force-feedback) controller (Fig. IV-22). An indexing switch was mounted on the position controller grip while both the rate and position controller hand grips had end effector closure switches.

The operators control console required a number of operational control and display hardware necessary for the operator to control a manipulator system. A preliminary analysis identified many of the control functions required and defined the related displays. Results of this analysis have been listed in Table VII-12.

Table VII-12 CDS/Manipulator Primary Controls and Displays

Function-Hardware	Associated Controls	Associated
Manipulator Motion Control		
Rate Controller	2-3 DOF Rate Hand Controllers 1 DOF Grip (Open/close)	6 Joint Forces 6 Joint Moments Grip Contact Grip Force
Position Controller	6 DOF Vertical Sliding Bilateral Controller 1 DOF Grip (open/close)	Grip Contact Grip Force

<u>Graphic Analysis</u>

A preliminary control/display st... was developed and reported in Ref. 13. This concept was ... JS envelope baseline for defining the non-interference controller working volume. The major concept assumptions and anthropometric data which impact the manipulator controller working envelopes have been evaluated and presented in Table VII-13.

The primary purpose of this analysis was to define the preliminary working volume available for a manipulator controller configuration when using operator comfort and nominal physical capability considerations as design guidelines. Of the two controller configurations considered the Apcllo rate type was evaluated first. The primary function identified to date for this type controller has been the translating and positioning input commands required to control the FFTS. Since the possibility also exists of using the same controllers for the manipulator and could be verified as feasible, then no additional operator working volume would be needed. The use of these controllers for manipulator control assumes first an auto pilot select capability on the FFTS and a high probability that the manipulator will be operated only during the docked mode.

The second controller considered was the 6-degree-of-freedom vertical sliding bilateral (force-feedback) controller. This unit was evaluated on a scaled graphic analysis which established the ideal man/machine working envelope. To do this required both a side view and top view analysis. Analysis results defined an available working envelope compatible with human engineering guidelines given in MSFC-STD-267A. A hand-grasp control was used to represent the neutral reference point of the resulting envelope.

The side view analysis as summarized in Fig. VII- 28 shows the operator's location relative to his work environment. Such factors as sitting through standing, console height, knee clearance, panel height, and seat height have been depicted. The maximum functional reach distances as well as the most effective work area for a seated operator was included. With the operator standing, the eye location correlates to the 95th percentile male and requires a floor adjustment of 20 cm (8 in) for the 5th percentile operator. As a minimum, foot and waist restraint systems were assumed as necessary to hold the operator in the desired

Table VII-13 Man/Machine Anthropometry Considerations to Derive Controller Operating Volume

Function	Value	Impact
Anthropometry Dimension	Accommodate 5th thru 95th percentile male	Provide comfort and optimum mobility
Eye - Elbow 5th percentile male 95th percentile male	 55.2 cm(21.8 in) 56.4 cm(22.3 in)	This data defines the reference point of the controller handgrip
Elbow-Grip Length 5th percentile male 95th percentile male	 32.5 cm(12.8 in) 37.6 cm(14.9 in)	Used to define optimum Controller Grip Use 95th percentile dimension for design
Hand Rise Level	20.3 cm(8 in)	Stay within visual
Hand Trans. Movement	±15.2 cm(±6 in)	Non-interferences distance between chest & control panel.
Hand Grasp Size (Minimum) (Maximum)	4.8 cm(1.5 in) dia. 7.6 cm (3.0 in) dia.	Define controller grip configuration
Hand Grip Strength Momentary Hold (RH) Sustained Hold (RH)	 28.6 Kg (63 lb) 19.1 Kg (42 lb)	

location. This also provides the operator some freedom to lean forward. With the operator seated, the fixed eve location requires a seat adjustment of 10 cm (4 in) in the vertical direction to accommodate the 5th percentile operator. Note also that the front panel's lower edge was defined by the operator's leg dimensions. This allows the position of the operator's legs to be adjustable from the full standing to the full seated configuration. The cross hatched area represents the vertical plane in which the controller can be positioned with no direct physical interference. The envelope as shown extends below the operator's waist which is not in the acceptable viewing envelope. However, this area can be used for controls, switches, etc., that can be hand operated.

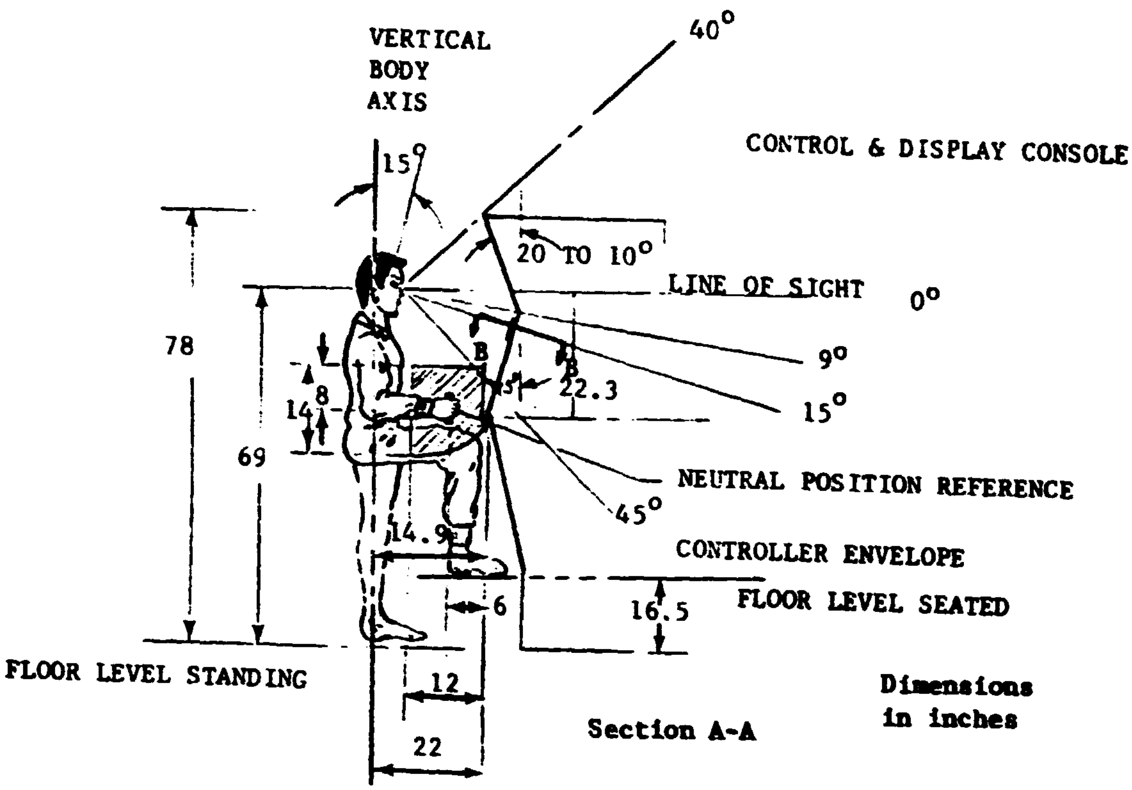


Figure VII-28 Side View, Vertical Console Section

The neutral position reference point was selected using the eye to elbow and elbow to grip distances for the 95th percentile male of 57.6 cm (22.3 in) and 37 cm (14.9 in). Note that the listed dimension of the eye to elbow for the 5th percentile male has a difference of only 1.3 cm (0.5 in). Thus it still provides the 5th percentile male a comfortable neutral arm position.

In general, the available volume can be described as a vertical cylinder with a 30 cm (12 in) diameter, 34 cm (14 in) height and a central neutral position reference.

The top view as shown in Fig. VII-29 indicates the horizontal relation-

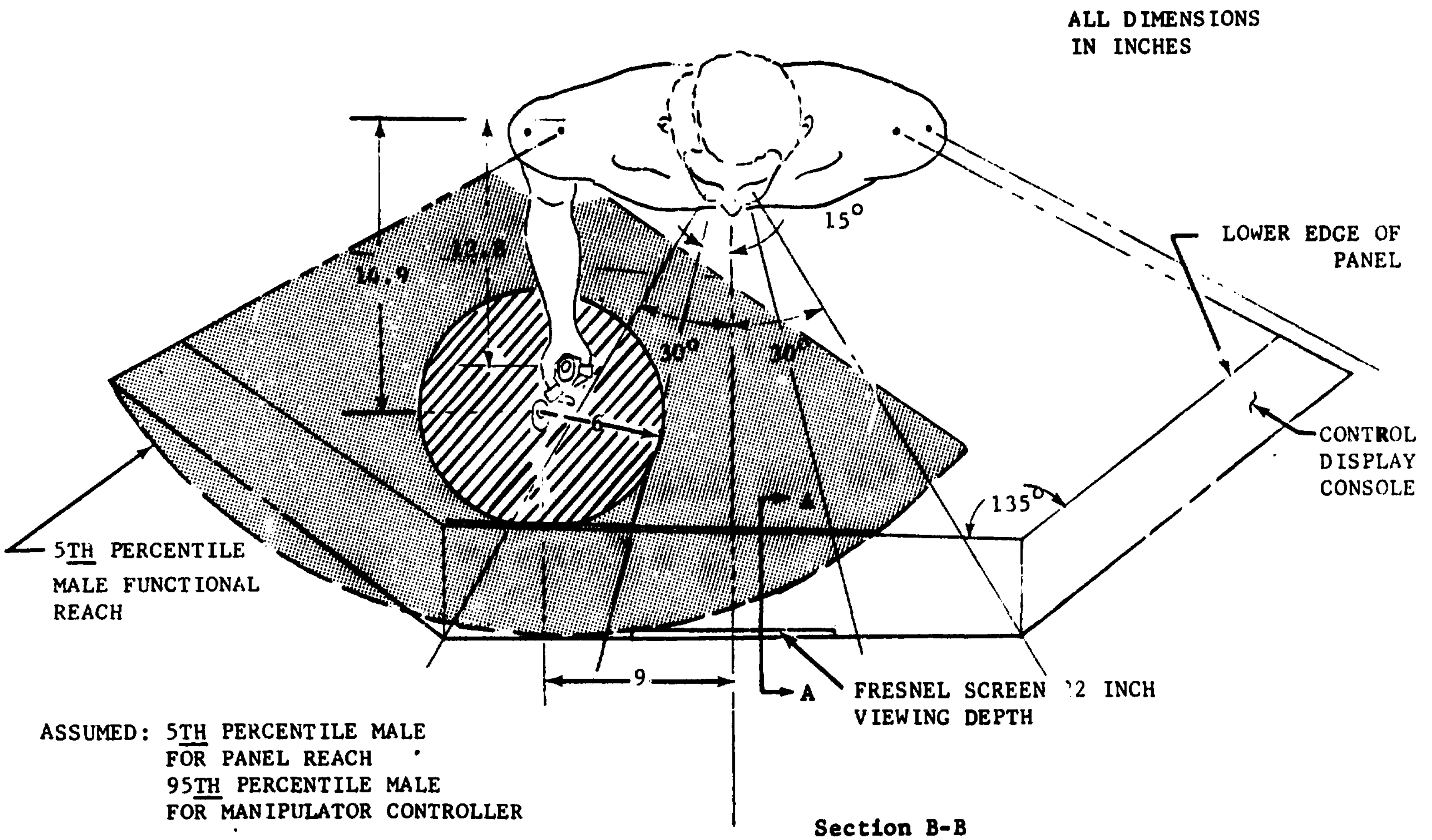


Figure VII-29 Top View, Horizontal Console Section ship of the operator to the console panels. In this layout the interaction of the horizontal functional arm reach, the fixed head viewing angles, and the Fresnel-stereo screen depth have been shown for a 5th percentile male. It can be seen by inspection of this layout that the dimensions indicated provides criteria that can be observed in designing for the panel width, the panel depths, and the attachment angles for side panels. The side panels have separate attach points and can be added or deleted as required by the mission.

Two areas have been identified on this drawing; the maximum reach envelope and the projected horizontal plane envelope in which the controller can be positioned. Through inspection a potential interference exists between the FFTS attitude controller and the manipulator controller. By using a retractable controller, the problem would be eliminated. This appears feasible since no task has been identified to date where both would be used simultaneously.

5. Simulations

During this study dynamic simulations were conducted and are reported in Appendix E. One of the simulation objectives was to define a dedicated manipulator control console for evaluating input hand controllers and related control and display elements.

The development of a representative dedicated manipulator console included the identification of control conditions and displays needed for optional manned manipulator control. A list of these items have been presented in Table VII-14 and can be seen on the completed console as per Fig. VII-30.

Table VII-14 Candidate Control and Display Elements

Control Functions	Displays
Position motion ratio (Translational) Position motion ratio (Rotational) Rate Control Gain (Translational) Rate Control Gain (Rotational) Force Ratio Wrist Torque ratio Terminal device closure rate Control Mode (Position or Rate) Hawk Mode (On/Off) Pan/Tilt of TV Camera Automatic Camera Track (On/Off) TV Camera Iris, focus, zoom	Stereo TV Mono TV Lens Zoom Setting Terminal Device % Closure Contact (light) Overdrive Condition Manipulator Joint Angles Contact Forces and Moments

Preliminary simulation results indicated that some of the instruments could be eliminated from panel mounting consideration or reduced complexity due to redundancy of functions or lack of use.

Items used very little were terminal device percent closure, contact light, manipulator joint angles, and a number of the indexing ratios. These items were common to both types of controllers evaluated; differences established for each controller include the following:

Rate Controller

Use 1, 3 Position Switch

Rate/Setting	High	Medium	Low
Translation (ft/sec)	1.5	0.6	0.3
Rotation (deg/sec)	10	5	1

Position Controller (Bilateral)

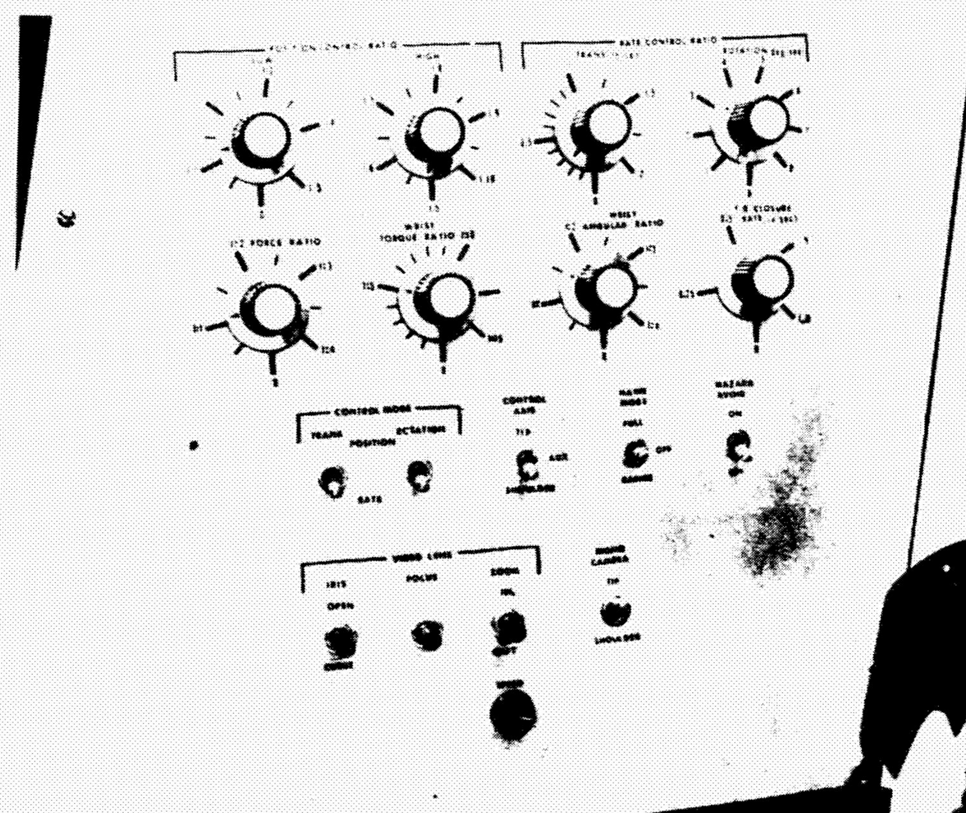
Use 1, 3 Position Switch

Ratio/Setting	High	Medium	Low
Translation	1:10	1:5	1:1
Rotation	1:3	1:2	1:1

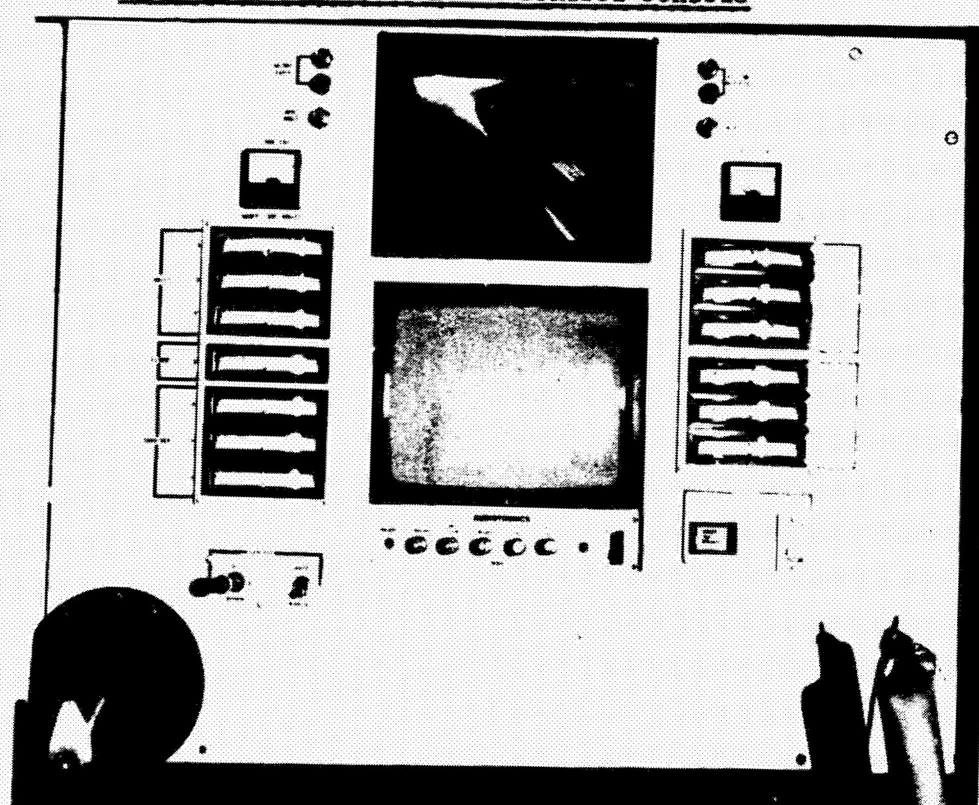
The rectilinear instruments to display the manipulator forces and moments are used for the rate controllers only. However, the position-type controller imposes a more severe volume penalty particularly when locating it on the orbiter flight deck.

6. Human Factor Considerations

This study has emphasized the human engineering considerations in defining the compatibility criteria necessary to evaluate adaptability



a. Side Panel for Simulation Control Console



b. Front Panel for Simulation Control Console

Figure VII-30 Dedicated Manipulator Control Console for Simulations of operator/control console interfaces. In doing this one must realize that the design of a panel layout is more complex than just arranging the selected control and display hardware on a panel surface. Many interactions must be considered; first are the interactions between the controls and displays and any associated interactions with the manipulator operator. Whenever the operator is involved in control and display functions his potential skills and senses must be considered. Some of these include: visual, auditory, tactile, kinesthetic, and motor skills. Other areas that must be considered involve items such as the environment around the operator (atmosphere temperature and velocity, noise, and open access), and force and motion requirements. In general, the considerations identified dealt with those having greatest impact on control and display panel layout definition. Sample guidelines and design factors are:

- Accommodate flight personnel at the CDS for the 5th to 95th percentile male using anthropometry dimensions as per MSFC-STD-267A;
- Adequate panel lighting and communications;
- Manual controls activated by hand operation;
- Controls located within the 5th percentile male operator functional reach;
- Ease of operation will be a primary design consideration for panel layout;
- Both functional and efficiency considerations will be given a high priority in panel design and layout;
- A prime consideration for panel design and layout is consistency relationship of controls and displays when moving from panel to panel within the limits imposed by their specific requirements;
- Where there is a choice between locating a control for right or left hand operation the right hand orientation will have priority;
- Provide restraint devices and adjustment capabilities for station operator(s) in various operational modes.

7. FFTS Integrated CDS Panel Layout

The panel layout methodology used in this study was to match the manipulator performance requirements with control and display functions. These functions in turn were reduced to a priority level and assigned to available flight type hardware. With this information the Preliminary Dedicated FFTS Panel Layout shown in Fig. VII-31 and reported in Ref. 12 was used as the starting point.

The next phase looked at this configuration with the intention of adding and deleting control and display elements as derived in this study. The evolution resulted in the reconfigured panel layout shown in Fig. VII-32.

a. Manipulator Performance Requirements - The general integration of the controls and displays required to operate a FFTS manipulator resulted in looking at support instruments on the Control and Display Console layout that perform both dedicated or dual functions. This requires the identification of systems other than the manipulator that are required to operate the FFTS. The FFTS can be separated into a number of prime systems; visual, propulsion, guidance/navigation, command communication, docking device and manipulator. Many vehicle system concepts applicable to the Free-Flying Teleoperator have been studied during the past decade. Each study has resulted in a final system design which included most of the above mentioned systems tailored to the particular mission/system requirements. Since this study emphasized the manipulator system, very little work was done on FFTS controls and displays that had little or no impact on manipulator controls. A review of some of the FFTS studies done to date (Ref. 1, 5 and 14) resulted in a preliminary system configuration description given in Table VII-15 with a number of the more feasible subsystem components assumed. The assumptions made are gross with the realization that considerable future effort is required in matching mission requirements with system capabilities.

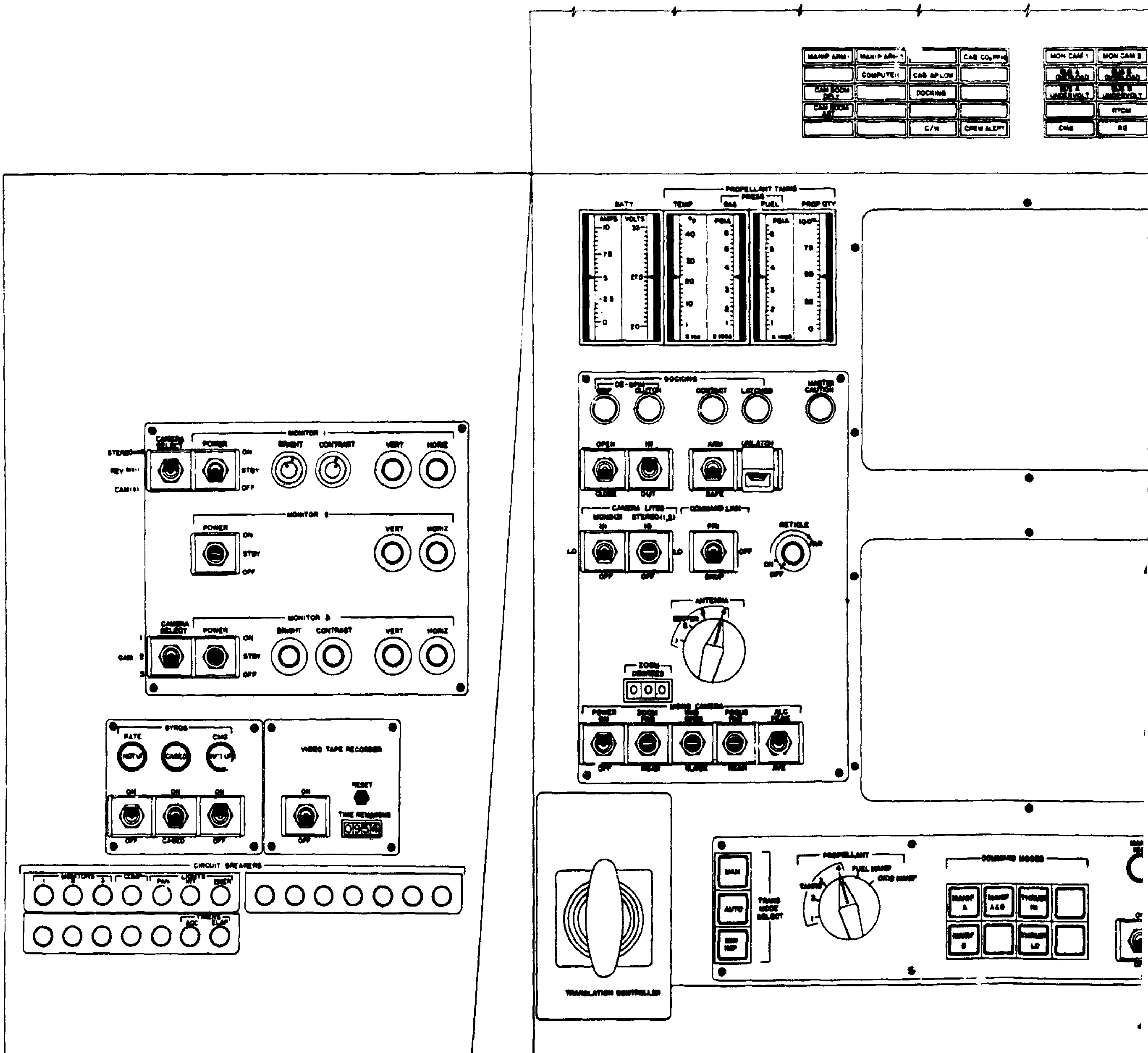
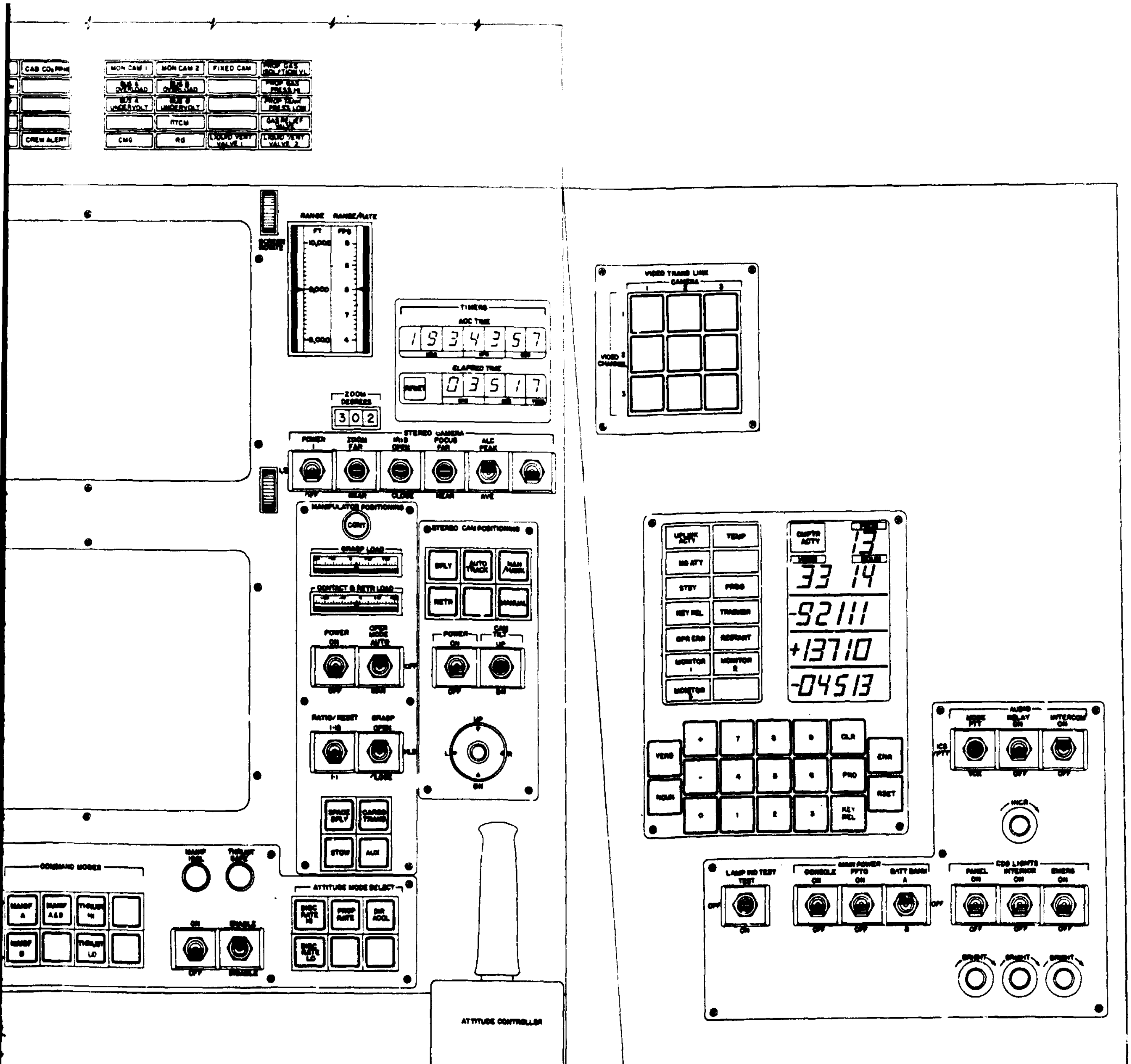


Figure VII-31 Preliminary Dedicated FFTS Panel


CREW ALERT
MON CAM 1
MON CAM 2
FIXED CAM
RTCM
CMG
RANGE
RANGE/RATE
TIMERS
ELAPSED TIME
ZOOM
DEGREES
302
STEREO CAMERA
POWER
ZOOM
IRIS
FOCUS
ALC
MANIPULATOR POSITIONING
GRASP LOAD
STEREO CAM POSITIONING
VIDEO TRANS LINK
CAMERA
TEMP
ATTITUDE MODE SELECT
COMMAND MODES
ATTITUDE CONTROLLER
MAIN POWER
CONSOLE
INTERCOM
ON
OFF
CLR

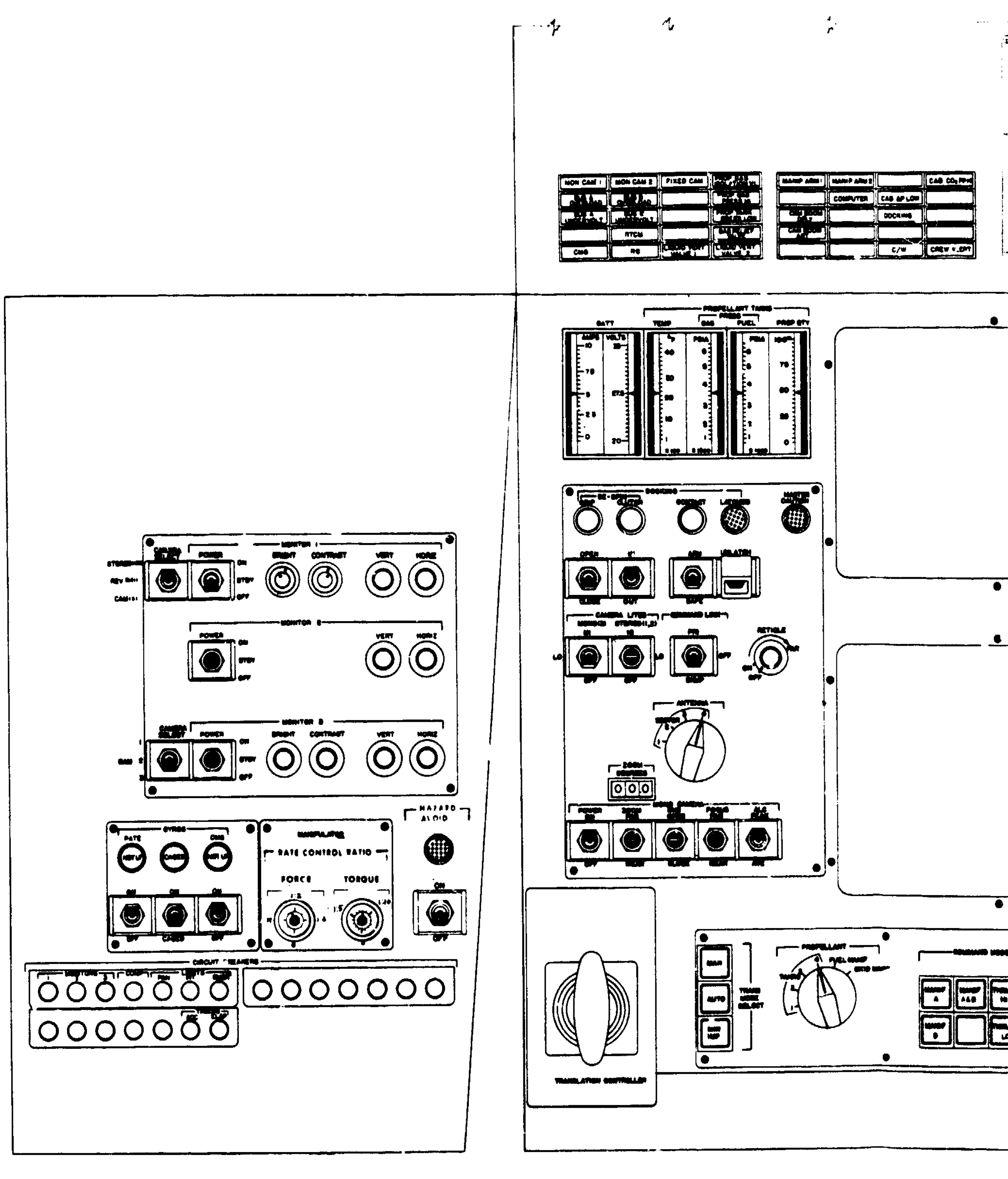
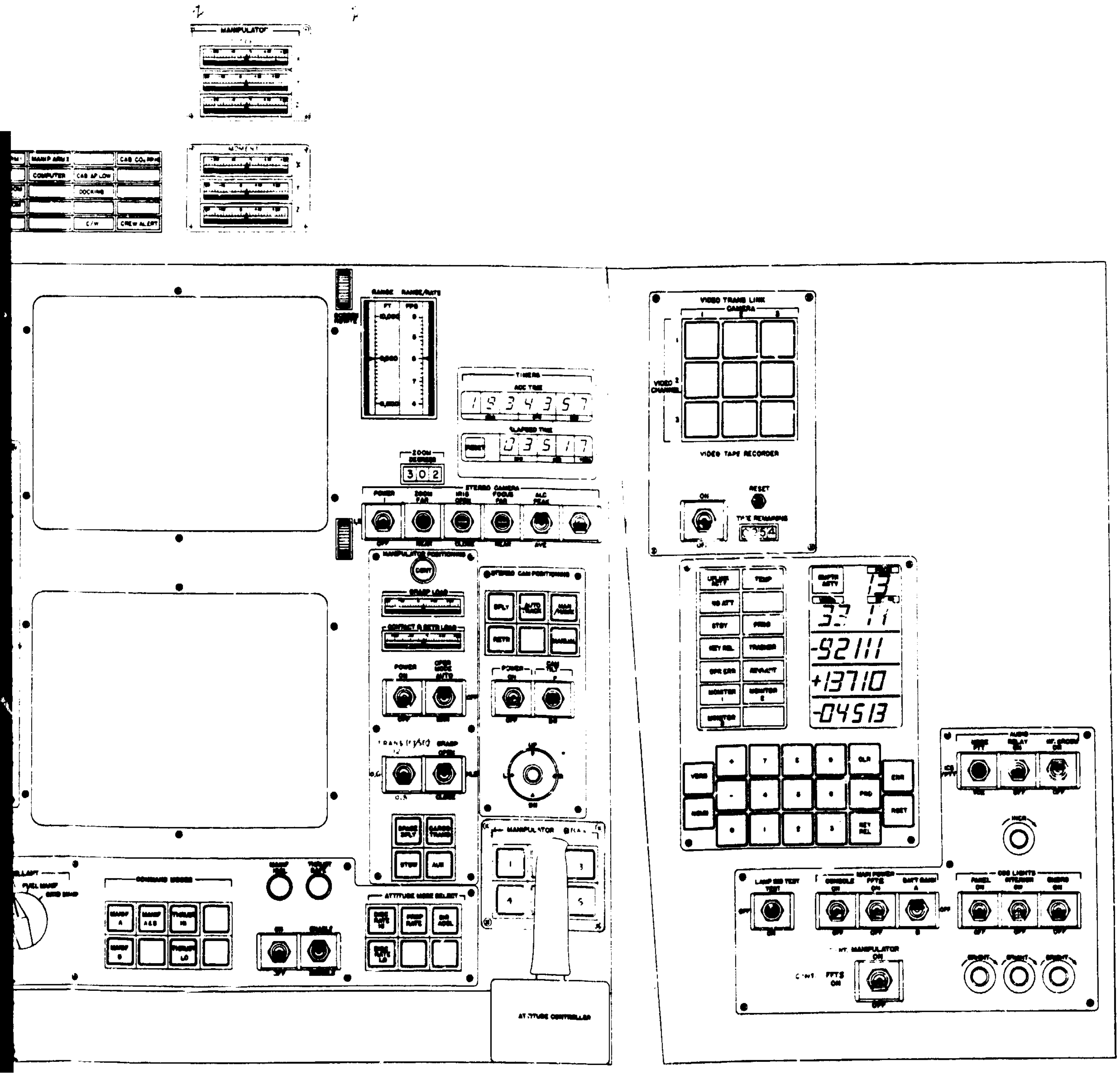


Figure VII-32 Reconfigured to Incorporate Manipulator Impacts

FOLDOUT FRAME 1



FOLDOUT FRAME 2

Table VII-15 FFTS Systems Summary

System	Design Concept	Control Functions
Visual	Indirect viewing technique using a hybrid stereo-mono displays	Camera selection, adjustments, and positioning (Pan and Tilt); Monitor selection and adjustments.
Propulsion	Primary propellant system using fuel tanks, thrusters, gas tanks, and associated valves	Control of thrusters, vents and main isolation valves. Display system-status. Fuel, pressure and temperature.
Electrical Power	Storage battery system with recharge capability	System activation and deactivation. Display system status: amps and volts.
Guidance, Navigation, and Control	Active three-axis control system with error sensing and active control torquing about three axes	Translation and attitude controllers with mode selects switches. Display, range, and range/rate data and gyro status.
Docking Mechanism	Probe and drogue latching system where the probe is passive and drogue is autolatch	Arm and unlatch docking device. Display system-status: contact, latched, and clutch status.
Manipulator	Structure designed to accommodate different types of manipulators	Hand controller with seven degree of freedom. Displays include status-lamps, contact, applied loads, and position select.

Basic manipulator C&D elements are listed in Table VII-14. As a result of the simulations this list has been narrowed down to a more optimum grouping of control and display elements. The type of hardware needed to satisfy the control and display requirements is shown in Table VII-16 along with general rationale for its selection. This Table shows both controller options and the commonality between the panel mounted control and display hardware. As indicated in this Table the same number of control and display items, with the exception of the manipulator forces and moments display, are required for both concepts.

Rectilinear instrument displays with fixed scales and moving pointers were selected for displaying manipulator forces and moments.

Selecting this type of display presented interesting areas in human engineering. One in particular was determining the effectiveness of a mixed arrangement of rectilinear instrument displays. Three arrangements of rectilinear displays were investigated; parallel vertical, parallel horizontal and a mixed vertical and horizontal arrangement. For each arrangement a uniform set of scales was used so that a quick visual check along the pointers would indicate

Table VII-16 Manipulator Control and Display Type Hardware and Selection Rationale

	Control or Display Requirement	Type Selected	Rationale
(1)	Rate-Rate Controllers	Honeywell Apollo Type Translation and Attitude Controllers	These controllers are suitable 3-axis and space qualified
	Translation Rate Control & Rotational Rate Control	3 position toggle switch on panel or hand controller	Gang on one switch for simplicity
	Joint Braking	Push button matrix (lighted)	Common Spacecraft Hdw.
	Force Ratio	Rotary Pot	Multiple Indexing Capability
	Torque Ratio	Rotary Pot	Multiple Indexing Capability
	Joint Forces	Rectilinear, moving point centered	Quick Detection
	Joint Moments	Rectilinear, moving point centered	Quick Detection
	Hazard Avoid	Toggle Switch, and Light	Common Spacecraft Hdw.
(2)	Position Controllers	New Vertical Sliding Bilateral Controller	6-axis controller for single hand operation
	Position Control Ratio (Trans.) Position Control Ratio (Rot.)	3 position toggle switch on panel or hand controller	Gang on one switch for simplicity
	Joint Braking	Push Button Matrix (lighted)	Common Spacecraft Hdw.
	Force Ratio	Rotary Pot	Multiple Indexing Capability
	Torque Ratio	Rotary Pot	Multiple Indexing Capability
	Hazard Avoid	Toggle Switch and Light	Common Spacecraft Hardware

any off-nominal conditions. The primary consideration relative to this approach was the operator's task requirement of monitoring ease and rapid detection of system changes. The most important conclusion drawn from the work deals with the realization of the need for more research on standardization of Shuttle payload control panel layouts. However, the study trends indicate very little difference between the all vertical or horizontal arrangement. It was also found that the mixed arrangement did not lend itself to as rapid a system change detection as the other two. Based on this information selection of vertical or horizontal displays was established as a function of panel location relative to the TV monitors. Horizontal displays were recommended for panel locations above the TV monitor while vertical displays were recommended for panel locations on either side of the monitor. Results of this evaluation were consistent with those of previous research performed and reported in Ref. 5. The problem still remains and further study should be conducted to determine whether perceptual grouping or change in orientation contributes more to optimizing panel layouts when task time and reduction of readout errors are prime evaluation parameters.

b. Projected CDS/Shuttle Orbiter Interfaces - The interfaces between the Shuttle orbiter and the CDS are primarily the two designated specialist stations on the flight deck of the orbiter. It is anticipated that the volume for the CDS to provide the required data for the specific mission will have been previously allocated. As with any CD station, the functional requirements to a large extent dictate the hardware, which in turn directly affects the station configuration. One environmental impact of considerable interest is the thermal and the illumination/display changes which occur continuously as the orbiter cycles from darkness to direct sunlight. The manipulators associated with the FFTS may be somewhat different from those that may be used with the Spacelab and experiments (LDEF and BESS).

Some of the more common interfaces and potential system impacts are presented in Table VII-17.

Table VII-17 Shuttle Integrated CDS Interfaces

Vehicle	Interfaces	System Impacts
Shuttle Orbiter	Payload specialist station	Available volume and functions will impact design
	Mission specialist station	Available volume and functions will impact design
	Flight deck	Shuttle-imposed requirements
	Shuttle ancillary equipment	Functional requirements will dictate hardware
	Lighting	Complete darkness to direct sunlight
	Electrical (power)	Assure compatibility
	Environmental (thermal, vibration, etc)	Design per Shuttle specifications
	Restraints	Lap and feet locations
	Communication equipment (voice and video)	Prime consideration for compatibility
	Man/machine	Anthropometry for 5 to 95 percentile male
	Manipulators (controls, displays)	Assure compatibility
	Data management	Compatible with data bus and display system

Since the payload specialist station on the Shuttle orbiter is one of the most restrictive as to available volume, it was selected as an example of how the panel configuration shown in Fig. VII-32 would look in the Shuttle (Fig. VII-33). With this arrangement the panel surface area provided is approximately 12,900 sq cm (2,000 sq in). As can be seen the operator would have to be located and restrained in the interdeck access openings. However, additional options may develop from on going NASA studies.

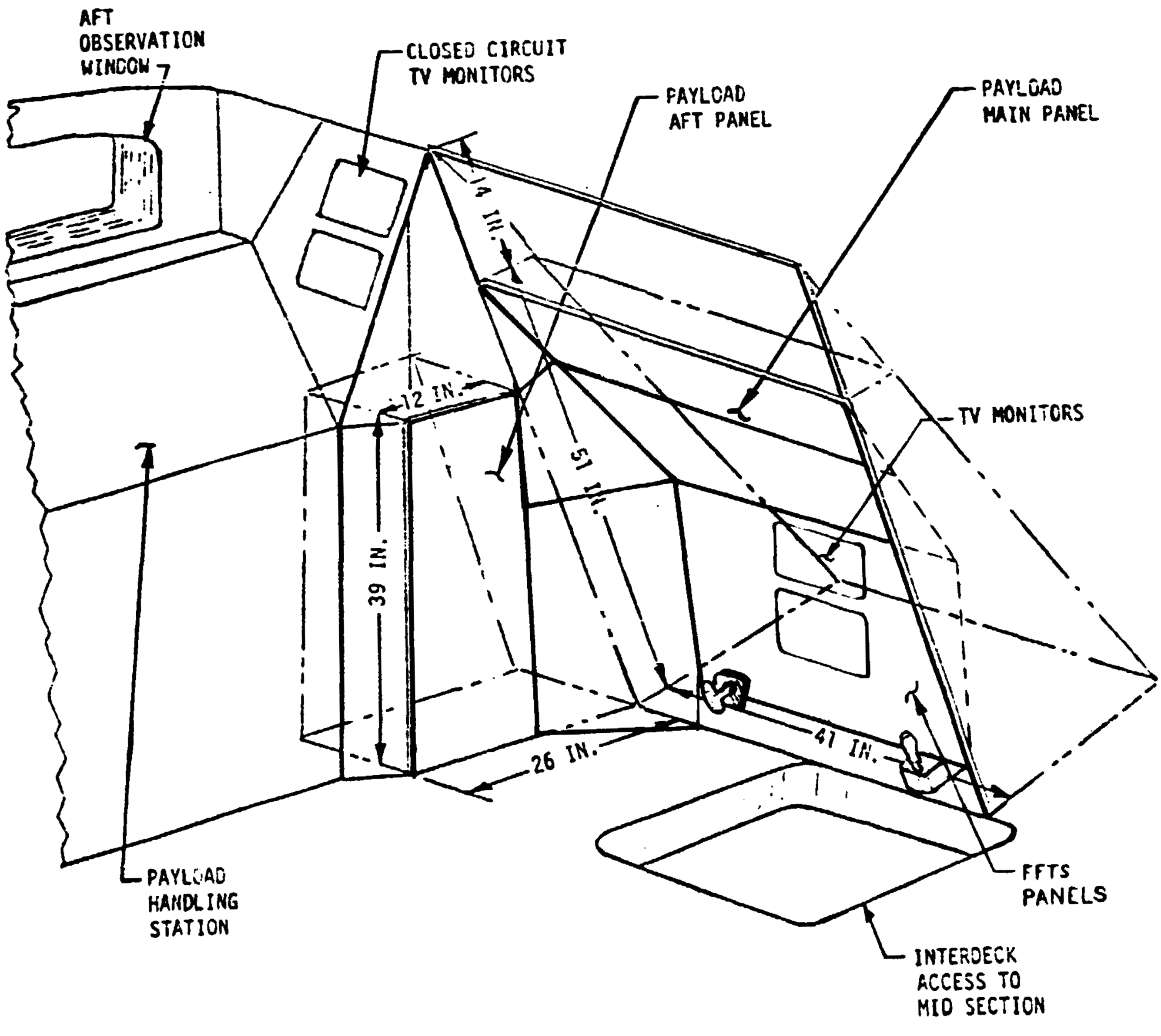


Figure VII-33 Payload Specialist Work Station

VIII. CONCLUSIONS AND RECOMMENDATIONS

A preliminary design of a manipulator system applicable to a Free Flying Teleoperator Spacecraft operating in conjunction with the Shuttle or Tug, was completed. The manipulator system, when developed for space applications in the near future, will provide an effective method for servicing, maintaining, and repairing satellites to increase their useful life.

The preliminary design is within today's state-of-the-art as reflected by typical "off-the-shelf" components selected for the design.

The manipulator system incorporates a new, but simple, control technique referred to as the range/azimuth/elevation rate-rate control system. This method was selected based upon the results of man-in-the-loop simulations.

The study identified several areas in which emphasis must be placed prior to the development and final design of the manipulator system. These areas are itemized below.

1. Man-in-the-Loop Simulations

The simulations conducted during this study were primarily directed toward evaluations of various control modes for servicing and maintenance type tasks. Although many recommendations concerning other system parameter values have been made, it is suggested that additional man-in-the-loop simulations be performed to finalize system parameters and establish total manipulator system operational characteristics. Other candidate control modes should be evaluated when considering other tasks to assure that the technique recommended in this report is still the optimum system (note that the preliminary design of the manipulator presented in this report does not prohibit the implementation of other control techniques).

It is also recommended that further man-in-the-loop simulations be performed to establish the following: operational procedures for doing all tasks; specific required operating parameters; optimum controls and displays (size, type, location); and specific rate hand controller characteristics, including possibly the evaluation of 3 degree of freedom isometric type rate controllers. Note that the controllers used in the simulations were "Apollo-type" and found to be "too-stiff" as these controllers were designed to provide the astronaut with a desired feel characteristic while wearing a pressurized suit.

Simulation data from these simulations will result in meaningful task timelines and manipulator actuator duty cycles. These areas will provide data for the thermal aspects and power requirements of the manipulator system.

2. Manipulator System Dynamic Analysis

A mathematical model of the manipulator system should be developed to enable a detailed analysis of the dynamic response of the system. Because of the nonlinearities inherent in manipulators, the stability of the control system/manipulator interactions must ultimately be verified by means of a computer, programmed with mathematical models of both the control system and the manipulator dynamics.

3. 1-g Manipulator Design Analysis

An analysis of the preliminary design of the 0-g manipulator should be conducted to determine the modifications required to operate the manipulator in a 1-g environment. The primary objective of the analysis would be to minimize modifications to the 0-g manipulator design, such that ground tests conducted will provide a high level of confidence in unit performance, design adequacy, and operator adaptability.

4. Detailed Actuator Trade Studies

The preliminary actuator designs can be optimized from several points of view. The additional simulation data, providing realistic duty cycles, can be incorporated into a design which may possibly require less power and hence, reduce actuator weight and thermal control complexibility, if required.

Additionally, it is recommended that a prototype actuator assembly be built. Empirical measurements on a dc torque motor with its gear head and load often provides more useful information than to try to use the basic motor specifications in conjunction with known load and gear head characteristics. Measurements on the motor in the system will provide parameters describing the actual system. Thus, the friction and windage of motor bearings, brushes, and load parameters are automatically lumped into one constant. Hence realistic data incorporating both actuator duty cycles and the physical components can be obtained.

5. Incorporation of Brakes within the Control System

The preliminary design provides "fail-safe" brakes which are manually operated except in the event of an FFTS power failure when they are automatically activated. Consideration should be given to the incorporation of the braking system within the control system. This technique may provide some advantage to the overall operational aspects of the manipulator system.

The "fail-safe" brakes consume power when released. Additionally, since the manipulator actuators require power during periods in which control commands are not issued (as a result of backdriveability) more power is required. Therefore, both the brake release "holding" and activator power requirements might be significantly reduced with the brakes controlled automatically.

6. FFTS Integrated System Trade Studies

Trade studies, based upon the total FFTS system should be conducted to provide a relative basis for allocation of power, weight, volume, acceptable EMI levels, etc., to the various FFTS subsystems. These allocations will enable the proper emphasis to be placed upon the manipulator subsystem during the development and final design phases.

7. Definition of FFTS/Satellite Interfaces

The interfaces between the FFTS and the satellites, in the areas of the docking device and work site, have not been defined at present. These depend highly on the satellite overall design and the awareness of the satellite designer on the availability of the FFTS for maintaining the satellite. It is therefore recommended that FFTS designers get with the "satellite user" community to establish compatible interfaces without significantly impacting the user's satellite design.

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APPENDIX A - SIX DEGREES OF FREEDOM MANIPULATOR ANALYSIS

1. Introduction

An analysis was conducted to establish the preferred six degrees of freedom manipulator configuration as a result of the numerous combinations of articulated and extendable joints that are possible with a six degree of freedom manipulator system. In general, to provide the general purpose manipulator with the capability of positioning the end-effector in any position or attitude, three translational and three rotational degrees of freedom are required. Additional joints are redundant and are only required to meet special situations (e.g., singularity avoidance, stowage limitations, etc).

The manipulator system was divided into two distinct areas, namely three degrees of freedom translation and three degrees of freedom rotation. This was based on manipulator control considerations in which separation of the translational and rotational variables results in an overall simpler system.

2. Translational Considerations

The definitions of the angles and coordinate system which are used in discussing the possible combinations of gimbals and extensions to translate the end-effector are shown in Figure A-1. Briefly roll, pitch, and yaw are the rotations about the X, Y, and Z axes, respectively. The origin of the coordinate system is at the shoulder or the elbow for the purposes of angle definition.

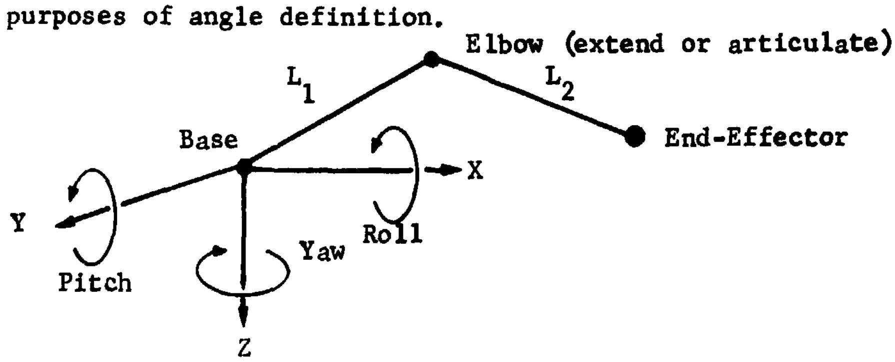


Figure A-1 - Coordinate System Reference

A matrix of base and elbow rotations for a two segment arm are shown in Table A-1. The table lists only two motions at the base, since this is the minimum number of motions required to move the elbow on a sphere of radius L_1, and a single rotation or extension at the elbow. Referring to Table A-1, a number of matrix locations are obviously impractical. For example, any two identical joints at the shoulder are essentially the same as one joint. Furthermore, the shoulder joint must allow positioning of the elbow anywhere on the sphere of radius L_1 to achieve full volume coverage. Thus, combinations with roll as the second base gimbal can also be immediately eliminated. Additionally, several matrix locations were eliminated due to the following problems: 1) spherical volume about the first axis that cannot be reached; 2) roll does not move the wrist; 3) elbow or end-effector moves only in one plane; 4) shoulder and elbow move only in the same plane; 5) two extensions in a row is the same as one, or 6) elbow moves only in the plane of the FFTS. In some cases two or more of the problems may apply to a given combination, but only one was used for elimination.

The results of the analysis are summarized in Table A-2. It should be noted that whether articulation or extension at the elbow is selected, the four configurations in each row are identical except for mounting locations. Thus, if a preference for elbow extension or articulation is established, only a single configuration will remain.

The desirability of an extendable or articulated elbow was investigated. As illustrated in Figure A-2, the articulated elbow has a considerable reach advantage over the extendable elbow. Basically, the articulated elbow provides continuous reach from zero to its maximum length, while the extendable elbow minimum range is limited to approximately 1/2 its maximum reach. Therefore, the articulated elbow is the preferred technique, and the baselined sequence, assuming the manipulator is mounted on the top of the FFTS, is yaw-pitch-pitch.

Table A-1 - Two Segment Manipulator Joint Matrix

Base	Elbow: Yaw	Pitch	Roll	Extend
Yaw Pitch	1	√	2	√
Yaw Roll	▬	▬	▬	▬
Yaw Yaw	▬	▬	▬	▬
Pitch Pitch	▬	▬	▬	▬
Pitch Yaw	√	1	2	√
Pitch Roll	▬	▬	▬	▬
Roll Pitch	1	√	2	√
Roll Roll	▬	▬	▬	▬
Roll Yaw	√	1	2	√
Extend Yaw	5	5	2	3
Extend Pitch	1	3	2	3
Extend Roll	▬	▬	▬	▬
Yaw Extend	4	4	2	3
Pitch Extend	1	4	2	3
Roll Extend	4	4	2	3
Extend Extend	▬	▬	▬	▬

1) Spherical volume about the first axis that cannot be reached.

2) Roll does not move the wrist.

3) Elbow or end-effector moves only in one plane.

4) Shoulder and elbow move only in the same plane.

5) Elbow moves only in the plane of the FFTS.

Legend

▬ Two identical joints in sequence is the same as one (base or elbow); or

▬ Roll at the second base joint does not move the elbow.

√ Acceptable Sequences

Table A-2 - Acceptable Joint Sequence Summary

Base	Elbow Articulation	Elbow Extension
Yaw Pitch	Pitch	Extend
Pitch Yaw	Yaw	Extend
Roll Pitch	Pitch	Extend
Roll Yaw	Yaw	Extend

3. Rotational Considerations

The second part of the manipulator joint ordering deals with rotation or attitude alignment of the end effector. Ideally, the manipulator wrist should provide only rotation at the tip with no translation. Also, continuous rotation of the wrist, a desirable feature, is most easily provided if roll is the last joint. Thus, the pitch, yaw, and roll axes of rotation and the end effector tip must be coincident as shown in Figure A-3. This configuration is impractical due to the mechanical bulk surrounding the end effector jaws which leads to interference problems.

The next alternative is to align two axes of rotation, pitch and yaw for example, and accept the translation or take out the translation using control logic. In this configuration, shown in Figure A-3, the amount of translation for each axis is the same but the configuration is cumbersome with limited joint travel.

The third case is where the axes of rotation are separated. This configuration is the lightest weight and simplest of the three configurations and the volume near the end effector jaws is not occupied by

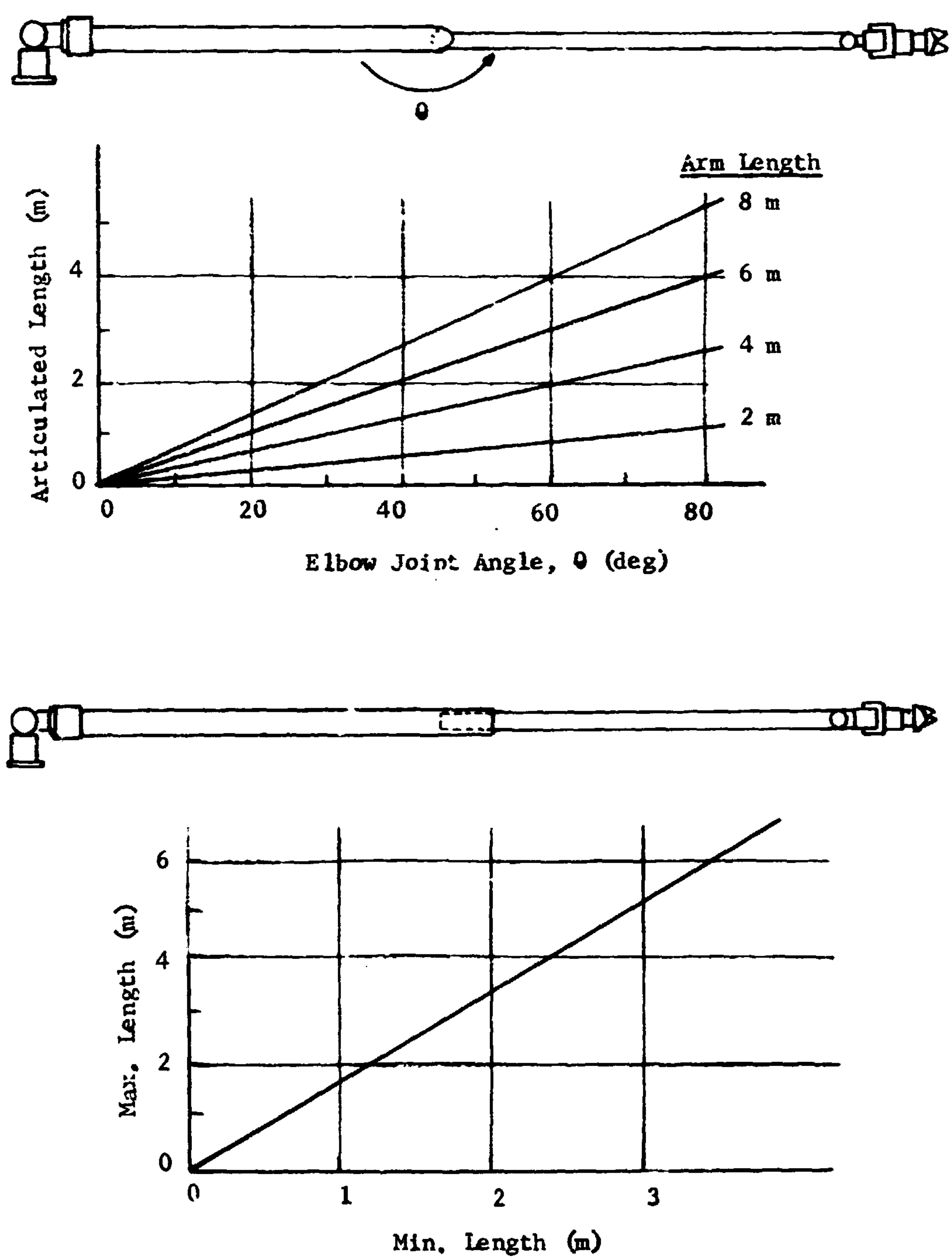
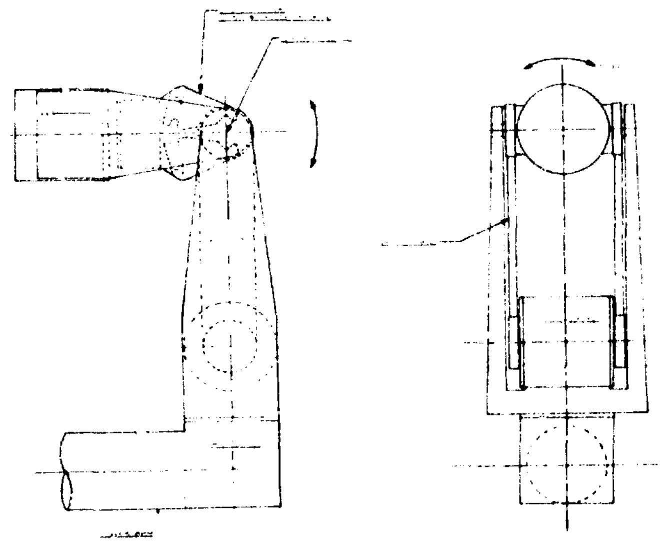
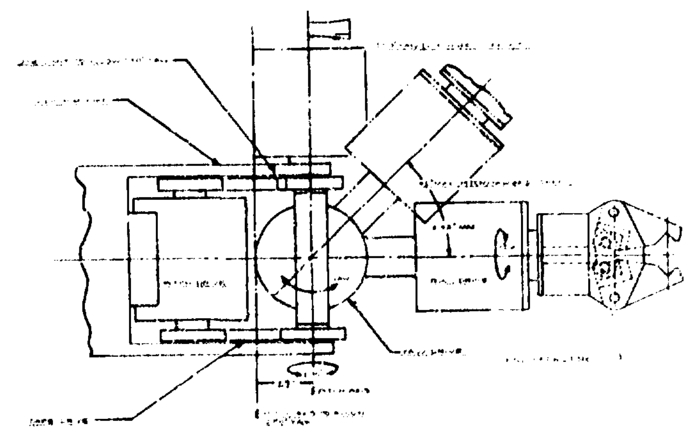


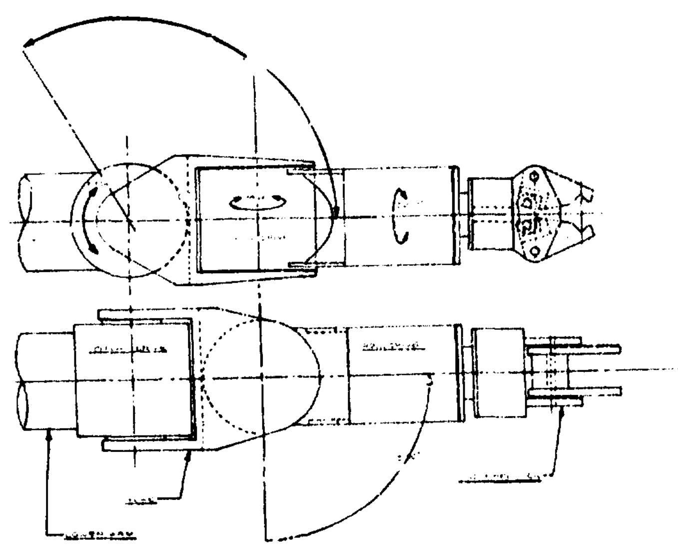
Figure A-2 - Extendable vs Articulated Reach



a) Coaxial Yaw-Pitch Roll Wrist



b) Coaxial Pitch/Yaw Wrist



c) Inline Pitch-Yaw-Roll Wrist

Figure A-3 Wrist Rotational Concepts

the joint drives. This inline configuration is preferred for the FFTS manipulator system and the sequence selected is pitch-yaw-roll. Roll is selected as the last gimbal to provide a continuous end-effector rotational capability and pitch is selected as the first gimbal as a result of potential control advantages based on the fact that shoulder and elbow pitch gimbals immediately precede the wrist.

4. Summary

The preferred six degrees of freedom manipulator configuration consists of a yaw-pitch gimbal sequence at the base, a pitch gimbal at the elbow, and a pitch-yaw-roll gimbal sequence at the wrist.

APPENDIX B - STATIC AND DYNAMIC MANIPULATOR ANALYSIS

1. Introduction

The strength of a manipulator can be characterized in two ways. First, one could measure the forces such a device can exert on any part of the surroundings to which it is anchored. The totality of all such forces is called the static force capability of the manipulator. Second, as manipulators are also used to transport objects, one could measure the accelerations the arm can impart to various masses, and, after multiplying by the mass of the object, arrive at the dynamic force capability of the manipulator. In general, the dynamic and static force capabilities are different, as illustrated by the following simple example.

Consider a single joint manipulator of length L and mass M_A capable of delivering a maximum torque T. This device is shown in static equilibrium with a force F_S in Figure B-1(a) and accelerating a mass M_P in Figure B-1(b). For static equilibrium

$$T = F_S L \tag{1}$$

and conservation of angular momentum requires

$$T = (M_P L^2 + M_A L^2/4)\ \ddot{\theta} \tag{2}$$

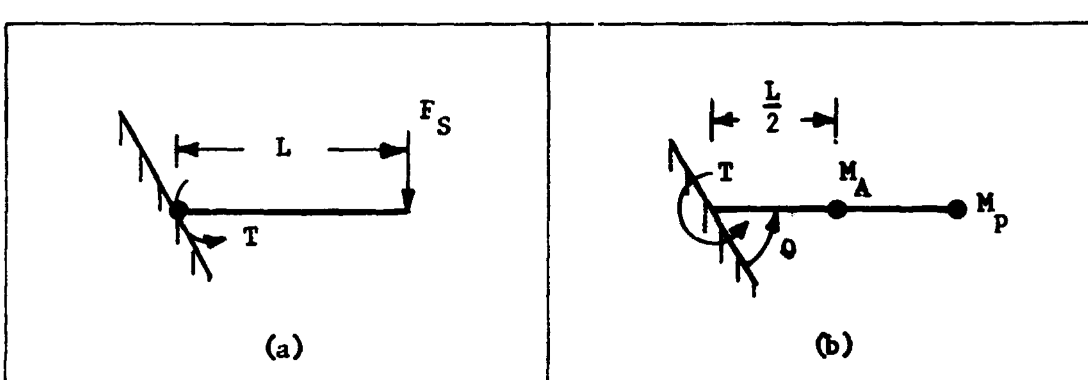


Figure B-1 - Single-Joint Manipulator

where the moments of inertia of both the arm and the payload about their mass centers have been neglected. The tangential acceleration is $L\ddot{\theta}$, and when multiplied by M_P to obtain the dynamic force, results in

$$F_D = M_P L\ddot{\theta} = \frac{T}{L^2 + \frac{1M_A}{4M_P} L^2} \tag{3}$$

Replacing T by $F_S L$ from Eq. (1) and rearranging terms, the dynamic/static force ratio becomes

$$\frac{F_D}{F_S} = \frac{M_P/M_A}{M_P/M_A + \frac{1}{4}} \tag{4}$$

This relationship is plotted in Figure B-2.

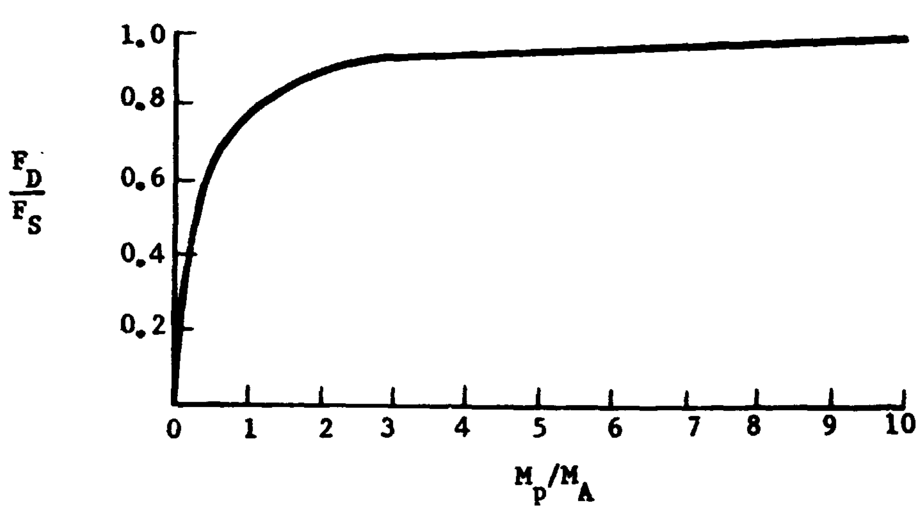


Figure B-2 - Force Ratio for Single-Joint Manipulator

Based on Eq. (4) and Figure B-2, it is seen that for payload masses three or more times greater than the arm mass, the static and dynamic force capabilities are effectively the same. For mass ratios less than three, the dynamic force capability is noticeably less than its static counterpart. In other words, if $M_P/M_A \geq 3$ the dynamic force requirement is dominant, but for $M_P/M_A < 3$, the static force requirement is sufficient.

In demonstrating that significant differences can exist between static and dynamic strength, the foregoing example raises the question: Should one base manipulator joint torque requirements on a static or a dynamic force capability? To answer this question, one must appeal to the primary function of the manipulator. For example, if the device is intended primarily to transport very massive objects, it would seem reasonable to base the design on dynamic considerations. In so doing, one could ensure the appropriate acceleration levels and thereby avoid unreasonably long task times. On the other hand, if the manipulator will be used, most of the time to retrieve and service relatively light modules from a spacecraft, then the prudent course would be to insure an appropriate static force capability. This is based on the likelihood that a manipulator, sufficiently strong to overcome static friction forces between module and spacecraft, will have adequate strength to transport the object at a reasonable rate.

In what follows, both the static and dynamic characteristics of an FFTS-type manipulator are examined. It was decided to characterize manipulator strength in terms of static force capability and then examine the resulting dynamic capabilities. This was done not only because the FFTS manipulator is intended primarily for module retrieval, but because static force requirements are generally easier to define.*

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*When joint torques are to be based on a dynamic requirement, one must first select a representative task and a reasonable task time. Because the acceleration capabilities of a manipulator depend on joint rates and position, as well as whether simultaneous or sequential joint motions are used, it is difficult to decide what constitutes a representative task and a reasonable task time (and thus avoid over or under designing the manipulator).

Further, as will be shown, it is possible to guarantee a minimum static force capability for any manipulator, regardless of force direction and point of application within the work volume of the manipulator.

2. Static Force Capability of Manipulators

The magnitude of a force that a manipulator can exert on its surroundings depends on the joint torque capability, manipulator configuration, and the direction of the force. It is therefore reasonable to search for a manipulator configuration and force direction which results in a minimum force magnitude. In finding such a combination, one can select joint torques to produce a desired force magnitude and be assured of at least the desired magnitude for any other configuration and force direction.

In locating the "weakest" configuration, it is assumed that a manipulator is composed of any number of arm segments, interconnected by one, two, or three degree-of-freedom joints. Associated with each joint gimbal is a motor capable of producing torques about the gimbal axis. One such manipulator in equilibrium with a tip force $\bar{F}$ is shown in Figure B-3. Now, it can be shown that equilibrium requires only that each motor produce that component of the joint torque which is parallel to the motor axis; the remainder being supported by the gimbal structure. The motor torques will be greatest when all the arm segments and the force vector lie in the same plane. For equilibrium of the system depicted in Figure B-3,

$$\bar{T}_X = - \bar{\rho}_X \times \bar{F} \qquad (5)$$

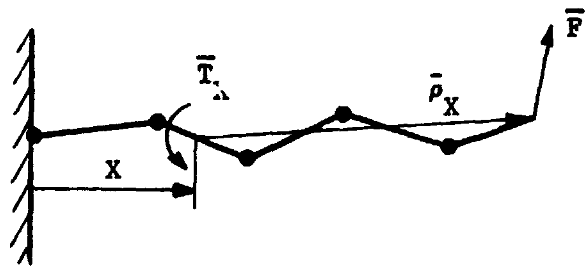


Figure B-3 - Multi-Joint Manipulator

from which it follows that $\bar{T}_X$ will be maximized simultaneously for all X when the manipulator is fully extended and the force vector is perpendicular to the extended arm. Conversely, a manipulator which when fully extended with each joint containing a motor axis perpendicular to the arm, and all such motor axes are parallel to one another, can exert a force of magnitude, F_M, in a direction perpendicular to both the aligned motor axes and the extended arm; then the same manipulator will be able to exert a force of at least a magnitude F_M, while in any other configuration and in any other direction in which the tip can move. An example of a "weakest" manipulator configuration is shown in Figure B-4.

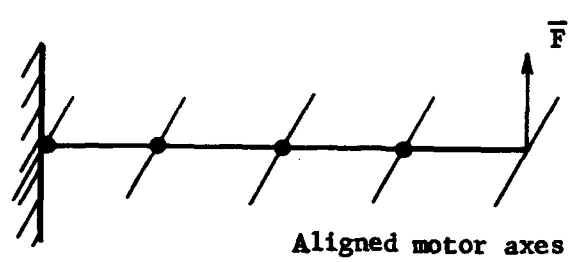


Figure B-4 - "Weakest" Configuration of a Manipulator

The existence of a "weakest" configuration for all articulated joint manipulators affords the designer a single criterion for manipulator strength comparisons, namely the <u>minimum tip force</u>. The minimum tip force is the maximum force (normal to the arm) that can be applied by the tip, on the environment, when the manipulator is in its weakest configuration.

Although a manipulator will most likely be designed for a specific minimum tip force, it is worth examining what tip forces are available in configurations other than the weakest. Typical variations in tip force with tip position are exhibited by the three-joint manipulator shown in Figure B-5. It is assumed that the three arm segments lie in the same plane and torques T_S, T_E and T_W at the shoulder, elbow and wrist joints respectively, maintain the arm in equilibrium with a force, F, also in the plane of the arm. It is also assumed that each joint contains a motor with an axis perpendicular to the plane of the arm. It follows that the plane depicted in Figure B-5 is the weakest plane of the manipulator.

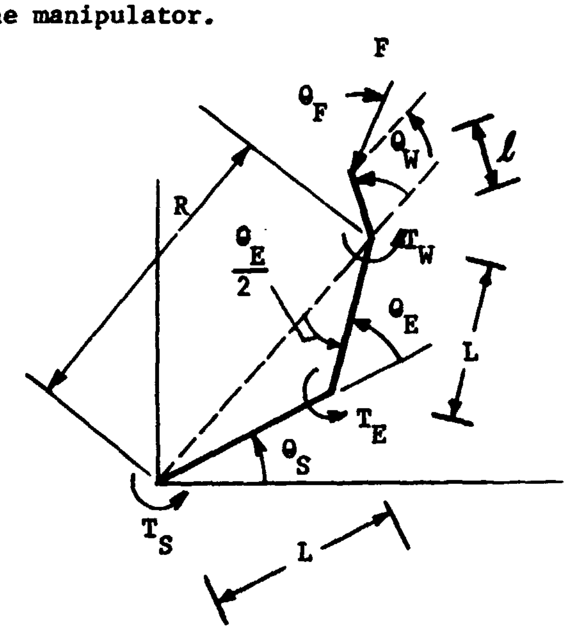


Figure B-5 - Three-Joint Manipulator

The equations of equilibrium are:

$$T_W = F\ell \sin(\theta_F - \theta_W) \tag{6}$$

$$\begin{aligned} T_E &= F \sin(\theta_F - \theta_E/2) \left[L + \ell \cos(\theta_W - \theta_E/2)\right] \\ &\quad - F \cos(\theta_F - \theta_E/2) \ell \sin(\theta_W - \theta_E/2) \end{aligned} \tag{7}$$

$$T_S = F \sin \theta_F (2L \cos \theta_E/2 + \ell \cos \theta_W) - F \cos \theta_F \ \ell \sin \theta_W \tag{8}$$

To keep matters simple, we shall consider only those configurations in which the end effector lies on the line connecting the shoulder to the wrist joint (i.e., $\theta_W = 0$). Equations 6 - 8 reduce to

$$T_W = F\ell \sin \theta_F \tag{9}$$

$$T_E = F(R/2 + \ell) \sin \theta_F - F_L \sqrt{1 - R^2/4L^2} \cos \theta_F \tag{10}$$

$$T_S = F(R + \ell) \sin \theta_F \tag{11}$$

where R is the distance between the shoulder and wrist joints

$$R = 2L \cos \theta_E/2 \tag{12}$$

The joint torques are determined by insisting the manipulator be capable of exerting at least a tip force F_M in all directions and at all points within the reach envelope. Toward this end, the arm is placed in its weakest configuration ($\theta_E = 0$, $\theta_F = 90^\circ$, and $R = 2L$) for which Eqs. 9, 10 and 11 yield

$$T_{WM} = F_M \ell \tag{13}$$

$$T_{EM} = F_M(L + \ell) \tag{14}$$

$$T_{SM} = F_M(2L + \ell) \tag{15}$$

where T_{WM}, T_{EM}, T_{SM} represent the maximum torque capability at the wrist, elbow, and shoulder joints respectively.

At this point, it is noted that the equilibrium equations 6 - 8 or 9 - 11 do not involve the shoulder angle θ_S. This means that the force capability for all points in the weakest plane can be determined simply by examining the variations in F with R and θ_F. In so doing, it is convenient to form the following ratios using Eqs. 9 - 15.

$$\frac{T_W}{T_{WM}} = f \sin \theta_F \tag{16}$$

$$\frac{T_E}{T_{EM}} = \frac{f}{1 + 2\ell_R} \left[(\rho + 2\ell_R) \sin \theta_F - \sqrt{1 - \rho^2} \cos \theta_F \right] \tag{17}$$

$$\frac{T_S}{T_{SM}} = \frac{F}{1 + \ell_R} = (\rho + \ell_R) \sin \theta_F \tag{18}$$

where

$$f = F/F_M \tag{19}$$

$$\ell_R = \ell/2L \tag{20}$$

$$\rho = R/2L \tag{21}$$

It follows that the torque capability of the arm will be exceeded if any of the ratios in Eqs. 16 - 18 exceed unity. Thus, the force capability of the manipulator can be determined by setting each of the joint torque ratios equal to unity and solving for the corresponding value of f. In other words

$$f_W = 1/\sin \theta_F \tag{22}$$

$$f_E = \frac{1 + 2\ell_R}{(\rho + 2\ell_R) \sin \theta_F - \sqrt{1 - \rho^2} \cos \theta_F} \tag{23}$$

$$f_S = \frac{1 + \ell_R}{(\rho + \ell_R)\sin\theta_F} \tag{24}$$

The subscripts W, E, and S denote the force ratio that limits the torque capability at the wrist, elbow, and shoulder joint respectively. The force capability corresponding to a particular value of ρ and θ_F is therefore the smallest of the three values given by Eqs. 22 - 24.

In passing, it is noted that because ℓ_R and ρ will always be less than or equal to unity, F_S will always be greater than or equal to F_W (as long as $\theta_W = 0$). This means that for all configurations of the manipulator with the end effector aligned with the line connecting the shoulder and wrist, the elbow or wrist torque capability will be exceeded before the shoulder torque and hence Eq. 25 can be eliminated from further consideration. The smaller of the two values, F_W and F_E, is plotted in Figure B-6 for various θ_F and ρ.

The results in Figure B-6 indicate that, for force directions other than perpendicular to the end effector, the manipulator generally becomes stronger as it approaches the outer limits of its reach envelope. This is the so-called "toggle effect" where extremely high forces can be produced by relatively low joint torques for this type of linkage. It is also noted that the values of ρ where the curves are horizontal correspond to configurations where the wrist motor is producing its maximum torque and the elbow and shoulder motors are producing less than peak values. The curved portions of the plots correspond to configurations in which the elbow joint torque is limited and the other two are below peak values.

3. Dynamic Capability of Manipulators

Having determined the joint torque requirements consistent with a minimum static tip force capability, F_M (see Eqs. 13 - 15), it is necessary to investigate the dynamic behavior of the system to insure these

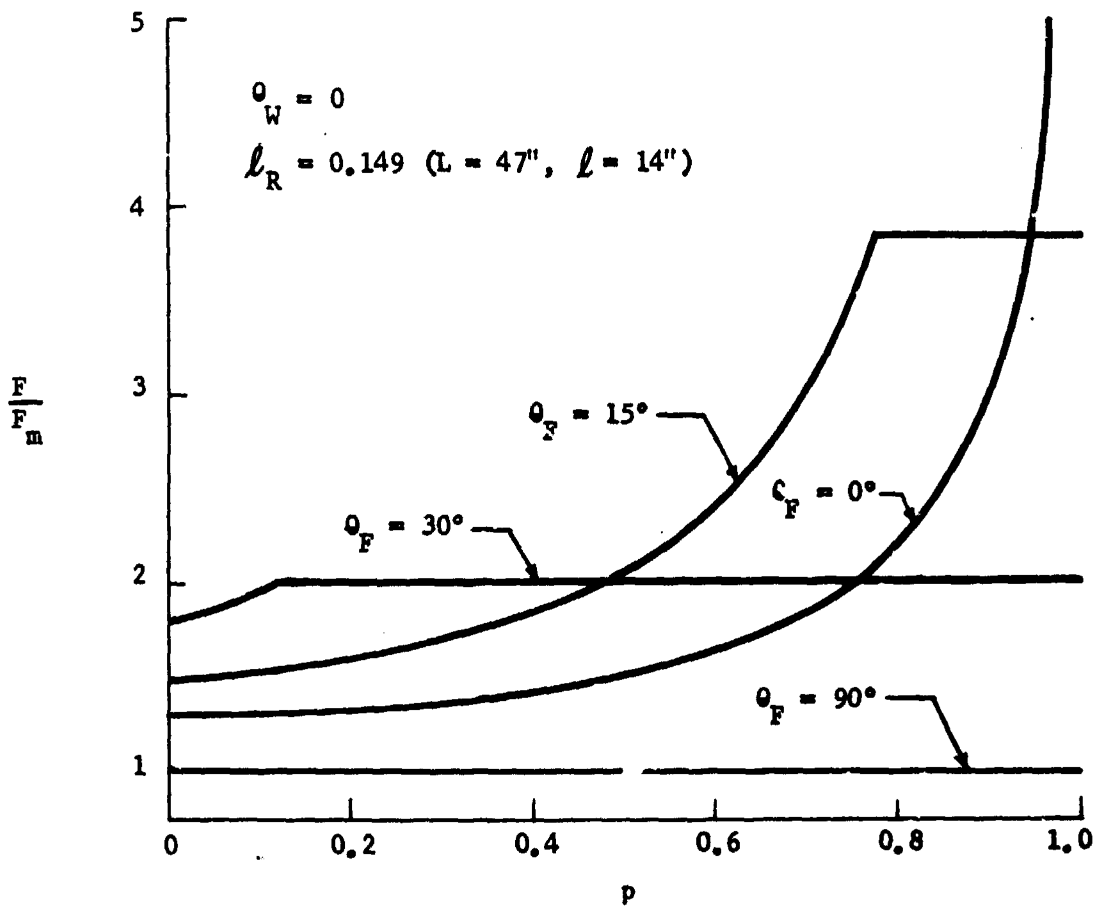


Figure B-6 - Static Force Capability for a Three-Joint Manipulator

torques provide adequate acceleration levels. As before, the investigation will be confined to motions within the weakest plane of the manipulator.

The system to be studied consists of a rigid payload attached to a three-joint manipulator as shown in Figure B-7. The payload is rigidly attached to the end effector of length ℓ at a point A. The combined

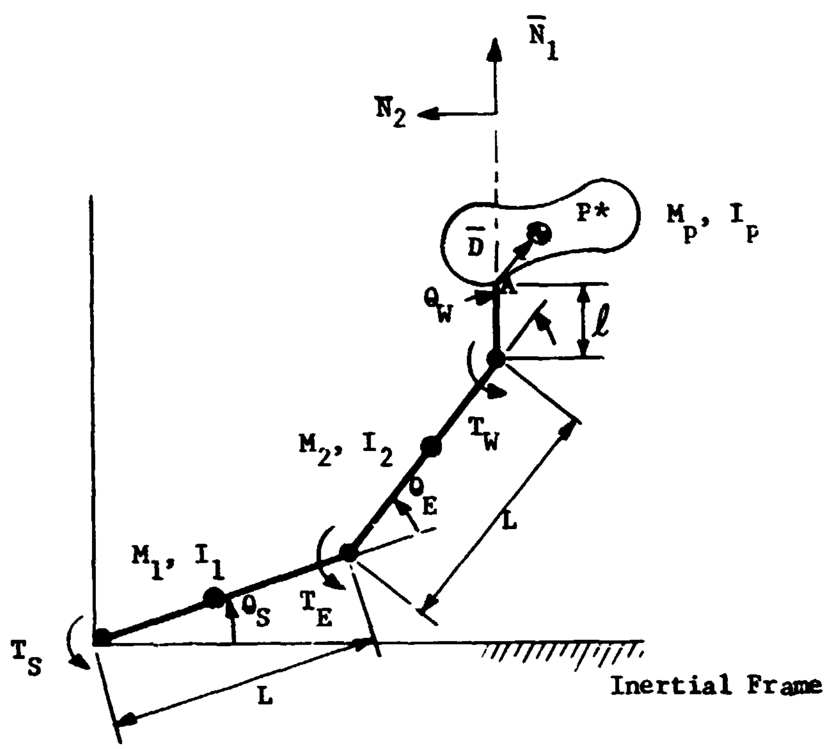


Figure B-7 - Three Joint Manipulator With Payload

mass of the end effector and payload is M_P and the combined mass center P^*, is located relative to A by the position vector, $\overline{D}$. The upper and lower arm segments are of length L and mass M_1 and M_2, respectively; their mass centers are presumed to coincide with their geometric centers. The moments of inertia of the three bodies relative to their mass centers and normal to the plane of motion are I_1, I_2, and I_P, respectively. Mutually perpendicular unit vectors, $\overline{N}_1$ an $\overline{N}_2$, rotate with the end effector as shown in Fig. B-7 and, for convenience, $\overline{D}$ is written

$$\overline{D} = D_1\overline{N}_1 + D_2\overline{N}_2$$

It is assumed that the body to which the manipulator is anchored is considerably more massive than the combined manipulator and payload, and therefore this body is presumed to be inertially fixed. The orientation of the upper arm relative to the inertial frame is given by θ_S; the angle between the lower and upper arm is θ_E; and θ_W is the angle between the end effector and lower arm. Finally, torques T_S, T_E, and T_W are presumed to act at the shoulder, elbow, and wrist joints, respectively.

The equations of motion governing the three joint angles have been derived using Lagrange's equations; the result can be written

$$\left[A_1 + A_2 + A_3 + 2F_E + 2F_W + 2F_{EW}\right] \ddot{\theta}_S + \left[A_2 + A_3 + F_E + 2F_W + F_{EW}\right]\ddot{\theta}$$
$$+ \left[A_3 + F_W + F_{EW}\right] \ddot{\theta}_W + 2\dot{\theta}_S \dot{\theta}_E (G_E + G_{EW}) + 2\dot{\theta}_S \dot{\theta}_W (G_W + G_{EW})$$
$$+ 2\dot{\theta}_E \dot{\theta}_W (G_W + G_{EW}) + \dot{\theta}_E^2 (G_E + G_{EW}) + \dot{\theta}_W^2 (G_W + G_{EW}) = T_S \qquad (25)$$

$$\left[A_2 + A_3 + F_E + 2F_W + F_{EW}\right] \ddot{\theta}_S + \left[A_2 + A_3 + 2F_W\right] \ddot{\theta}_E + \left[A_3 + F_W\right] \ddot{\theta}_W$$
$$- \dot{\theta}_S^2 (G_E + G_W + G_{EW}) - \dot{\theta}_E^2 G_W + \dot{\theta}_W^2 G_W - 2\dot{\theta}_S \dot{\theta}_E G_W$$
$$+ \dot{\theta}_S \dot{\theta}_W G_W = T_E \qquad (26)$$

$$\left[A_3 + F_W + F_{EW}\right] \ddot{\theta}_S + \left[A_3 + F_W\right] \ddot{\theta}_C + A_3 \ddot{\theta}_W - \dot{\theta}_S^2 (G_W + G_{EW})$$
$$- \dot{\theta}_E^2 G_W - 2\dot{\theta}_S \dot{\theta}_E G_W = T_W \qquad (27)$$

where

$$A_1 = I_1 + (M_1/4 + M_2 + M_P)L^2$$

$$A_2 = I_2 + (M_2/4 + M_P L^2)L^2$$

$$A_3 = I_P + M_P \left[(\ell + D_1)^2 + D_2{}^2\right]$$

$$F_E = (M_2/2 + M_P)L^2 \cos \theta_E$$

$$G_E = -(M_2/2 + M_P)L^2 \sin \theta_E \tag{28}$$

$$F_W = M_P L \left[(\ell + D_1) \cos \theta_W - D_2 \sin \theta_W\right]$$

$$G_W = - M_P L \left[(\ell + D_1) \sin \theta_W + D_2 \cos \theta_W\right]$$

$$F_{EW} = M_P L \left[(\ell + D_1) \cos (\theta_E + \theta_W) - D_2 \sin (\theta_E + \theta_W)\right]$$

$$G_{EW} = - M_P L \left[(\ell + D_1) \sin (\theta_E + \theta_W) + D_2 \cos (\theta_E + \theta_W)\right]$$

Equations 25 - 27 can be used in two ways. First, if one has in mind a particular task to be accomplished, it is possible to derive the appropriate time histories for the joint angles, evaluate the left hand sides of Eqs. 25 - 27 and thereby obtain time histories for the joint torques. This information can then be used to arrive at the torque requirements for the arm. On the other hand, if the joint torques are assumed to be based upon static considerations, Eqs. 25-27 are useful in determining the dynamic capabilities of the manipulator. The remainder of this section will be devoted to the latter application.

In discussing the dynamic capability of a manipulator, one must first choose a standard of measurement; in this case, the joint angular accelerations, $\ddot{\theta}_S$, $\ddot{\theta}_E$, and $\ddot{\theta}_W$ will be used. If one so desires, these quantities can be related to the linear acceleration of any point on the arm or payload by employing the appropriate kinematical equations.

Inspection of Eqs. 25 - 27 reveals that the angular accelerations depend on joint rates in addition to joint position and torque. To eliminate the dependence on joint rates, we shall limit this investigation to accelerations from a state of rest or states for which the joint rates are sufficiently small that second order terms in these quantities can be neglected. When this is the case, Eqs. 25 - 27 can be written

$$\begin{aligned} C_{11}\ddot{\theta}_S + C_{12}\ddot{\theta}_E + C_{13}\ddot{\theta}_W &= T_S \\ C_{21}\ddot{\theta}_S + C_{22}\ddot{\theta}_E + C_{23}\ddot{\theta}_W &= T_E \\ C_{31}\ddot{\theta}_S + C_{32}\ddot{\theta}_E + C_{33}\ddot{\theta}_W &= T_W \end{aligned} \tag{29}$$

where the C_{ij} are the coefficients of the first three terms in Eqs. 25 - 27.

The angular acceleration capability of the ma.. .ilator will be studied for the following modes of operation

$$\begin{aligned} \ddot{\theta}_S &= N_S\alpha \\ \ddot{\theta}_E &= N_E\alpha \\ \ddot{\theta}_W &= N_W\alpha \end{aligned} \tag{30}$$

In other words, the investigation will be confined to cases in which the joint accelerations are a co. ..ant multiple of one another. Substitution from Eq. 30 into 29 yields

$$\frac{\alpha_S}{F_M} = \frac{(2L + \ell)}{C_{11}N_S + C_{12}N_E + C_{13}N_W}$$

$$\frac{\alpha_E}{F_M} = \frac{(L + \ell)}{C_{21}N_S + C_{22}N_E + C_{23}N_W} \tag{31}$$

$$\frac{\alpha_W}{F_M} = \frac{\ell}{C_{31}N_S + C_{32}N_E + C_{33}N_W}$$

where the joint torques, T_S, T_E, and T_W have been replaced by their maximum values consistent with the minimum static tip force capability F_M (see Eqs. 13 - 15). The subscripts, S, E, and W on α in Eqs. 31 denote the maximum acceleration level that can be maintained by the shoulder, elbow and wrist torques, respectively. Thus, one can determine the maximum value of α/F_M corresponding to a particular choice of N_S, N_E and N_W by computing the right hand sides of Eqs. 31 and choosing the lowest value. By repeating this process for all arm configurations, one can obtain a map of α/F_M corresponding to a particular combination of N_S, N_E and N_W.

In what follows, the angular acceleration capability will be determined for all configurations in which the end effector is aligned with the line connecting the shoulder and wrist joint. In other words, for configurations in which $\theta_W = -\theta_{E/2}$ (see Figure B-7). In the process it is assumed that the upper end and lower arm segments are identical, the moment of inertia I_1 is small compared to $M_1L^2/4$, and that the end effector is aligned with a line connecting the wrist joint with the mass center of the payload. When this is the case, one can write

$$M_1 = M_2; \qquad I_1 = I_2 = 0; \qquad D_2 = 0 \tag{32}$$

and, by making use of Eq. 12, Eqs. 31 can be rewritten

$$\frac{\alpha_S}{F_M} = (2 + \beta_2)/\left\{\left[\beta_4 + (\beta_2 + \beta_3)^2\right](N_S + N_E + N_W) + \frac{\beta_1}{4}(2N_S - N_E)\right.$$
$$\left. + (\beta_2 + \beta_3)\left[4N_S + 3N_E + 2N_W\right]\rho + (\beta_1 + 2)\left[2N_S + N_E\right]\rho^2\right\}M_P L \tag{33}$$

$$\frac{\alpha_E}{F_M} = (1 + \beta_2)/\left\{\left[\beta_4 + (\beta_2 + \beta_3)^2\right](N_S + N_E + N_W) - \frac{\beta_1}{4}N_S\right.$$
$$+ (\beta_1/4 + 1)N_E + (\beta_2 + \beta_3)\left[3N_S + 2N_E + N_W\right]\rho \tag{34}$$
$$\left. + (\beta_1 + 2)N_S \quad \rho_2\right\}M_P L$$

$$\frac{\alpha_W}{F_M} = \beta_2/\left\{\left[(\beta_4 + (\beta_2 + \beta_3)^2\right](N_S + N_E + N_W) + (\beta_2 + \beta_3)\right.$$
$$\left.\left[2N_S + N_E\right]\rho\right\}M_P L \tag{35}$$

where

$$\begin{aligned} \beta_1 &= M_1/M_P \\ \beta_2 &= \ell/L \\ \beta_3 &= D_1/L \\ \beta_4 &= I_P/M_P L^2 \\ \rho &= R/2L \end{aligned} \tag{36}$$

The maximum angular acceleration capability has been determined for the following modes of operation (for all values of ρ):

Mode A: $N_S = N_E = N_W = 1$

All joints accelerating in the same direction with equal magnitudes; i.e., $\ddot{\theta}_S = \ddot{\theta}_E = \ddot{\theta}_W = \alpha$

Mode B: $N_S = N_E = 0$, $N_W = 1$

Shoulder and elbow joints fixed, wrist joint accelerating; i.e.. $\ddot{\theta}_S = \ddot{\theta}_E = 0$, $\ddot{\theta}_W = \alpha$

Mode C: $N_S = N_W = 0$, $N_E = 1$

Shoulder and wrist joints fixed, elbow joint accelerating; i.e., $\ddot{\theta}_S = \ddot{\theta}_W = 0$, $\ddot{\theta}_E = \alpha$

Mode D: $N_E = N_W = 0$, $N_S = 1$

Elbow and wrist joints fixed, shoulder joint accelerating; i.e., $\ddot{\theta}_E = \ddot{\theta}_W = 0$, $\ddot{\theta}_S = \alpha$

It is noted that in the above operational modes, when a joint is said to be fixed, it is understood that the necessary constraint torque is supplied by the torque motor (as opposed to a brake or locking device).

Results have been obtained for the following sets of data shown in Table B-1.

The data for the loaded arm reflect the 150 kg, 1 meter cube payload, relative to which the mass of the end effector has been neglected. The unloaded arm data reflect an end effector mass of .62 slugs located half way between the wrist joint and end effector tip.

Table B-1 - Inertia Properties and Geometry for Loaded and Unloaded Arm

Loaded Arm	Unloaded Arm
$M_1 = M_2 = .698$ slugs	$M_1 = M_2 = .698$ slugs
$L = 47''$, $\ell = 14''$, $D_1 = 19.7''$	$L = 47''$, $\ell = 7''$, $D_1 = 0$
$M_P = 10.27$ slugs	$M_P = .62$ slugs
$I_P = 18.43$ slug-ft^2	$I_P = 0$

Using the above data, one can evaluate Eqs. 33 - 35 for each of the operational modes A - D for values of ρ between 0 and 1. The smallest of the three values of α/F_M (and hence the maximum value for the manipulator) are plotted for each case in Figures B-8 and B-9.

Looking first at Figure B-8, it is seen that the acceleration capability generally increases with decreasing values of ρ. This is due to the decreasing moment of inertia each joint must accelerate as the wrist joint approaches the shoulder joint. It is also noted that all of the acceleration levels in Figure B-8 are a result of limiting the wrist torque capability. This will generally be the case with heavier payloads when the joint torques of the manipulator are based on a minimum static tip force requirement. The cause of this apparent dynamic "weakness" in the wrist joint can be found by considering a massless, single-joint, manipulator such as the one shown accelerating a payload of mass, M_P, and moment of inertia, I_P, in Figure B-10. Assuming the joint torques are based on a minimum static tip force requirement, F_M, the torque capability of a joint located a distance X from the shoulder is given by

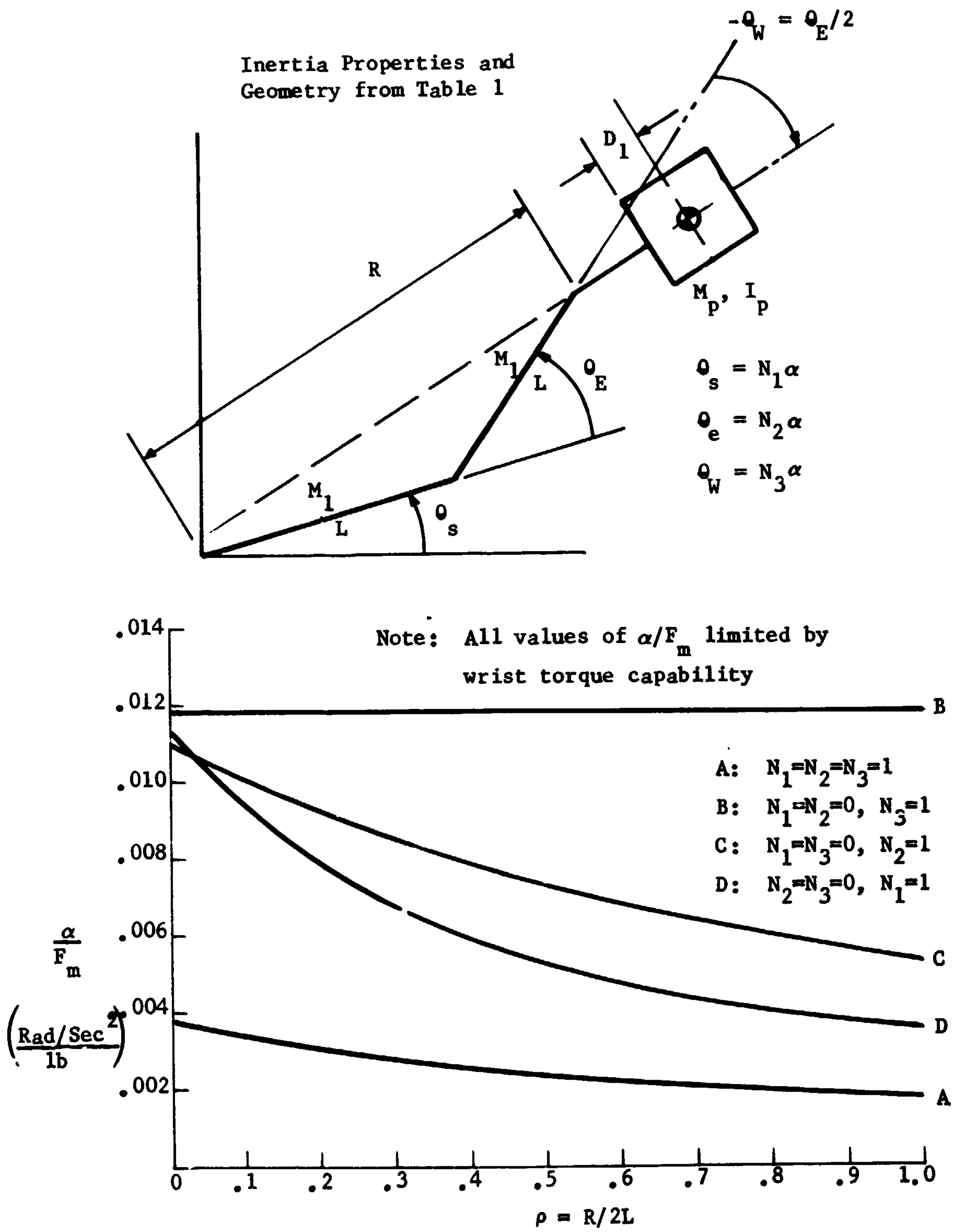


Figure B-8 - Acceleration Capability - Loaded Arm

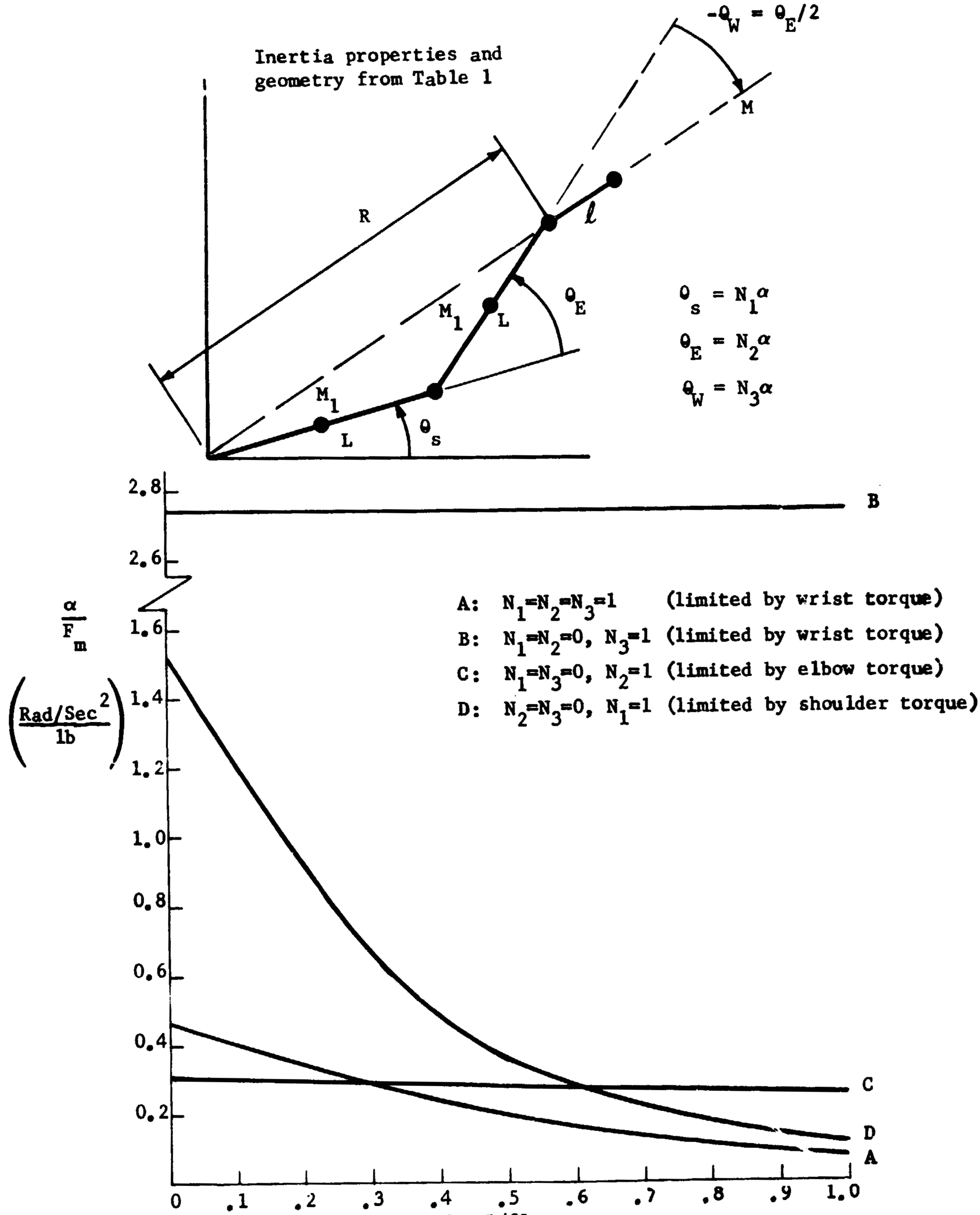


Figure B-9 - Acceleration Capability - Unloaded Arm

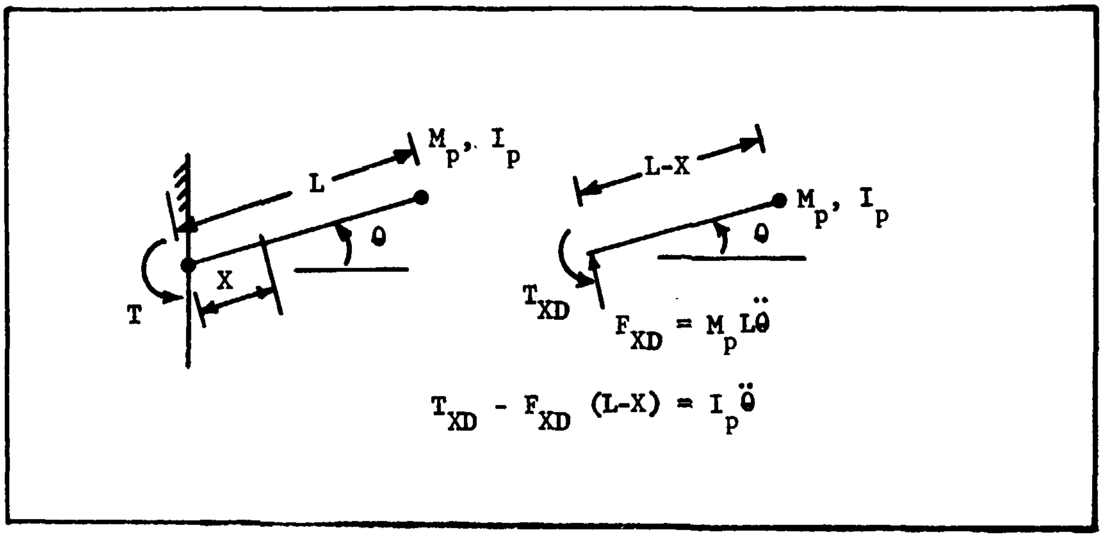


Figure B-10 - Single-Joint Manipulator with Payload

$$T_{XS} = F_M(L - X)$$

and using momentum principles, for an angular acceleration $\ddot{\theta}$, the same joint must produce

$$T_{XD} = \left[I_P + M_P L(L - X)\right] \ddot{\theta}$$

The ratio of the two is then

$$\frac{T_{XD}}{T_{XS}} = \left[\frac{I_P}{L - X} + M_P L\right] \frac{\ddot{\theta}}{F_M}$$

from which it can be seen that, for a given $\ddot{\theta}$ joints located furthest from the shoulder (i.e., for X approaching L) must produce the greatest torques in relation to their static torque capability.

Conversely, the limiting value of $\ddot{\theta}/F_M$ will result from exceeding the torque capability of the outermost joint. The reason for all this is seen to be the equal impact (for all X) of I_P on the dynamic torque capability, T_{XD}, while the static torque capability, T_{XS}, diminishes to zero as X approaches L.

Thus, if one should find the acceleration capability for the heavier payloads to be inadequate, one does not necessarily have to increase the torque capability of all the joints (and thus the static tip force capability). On the contrary, it is possible to effect increases in angular acceleration levels by increasing the torque capability of only the outermost joints.

The acceleration levels for the unloaded arm are shown in Figure B-9 and are seen to be approximately two orders of magnitude greater than those for the loaded arm. In this case, because the moment of inertia I_P has been neglected, the acceleration levels are not all limited by the wrist torque.

Finally, it is informative to examine the times required to complete a task which does not involve the centripetal and coriolis terms in Eqs. 25 - 27. One such task involves a rotation about the shoulder joint through an angle θ_S while the arm is fully extended (i.e., $\theta_E = \theta_W = 0$) and the mass center of the payload lies along an extension of the end effector (i.e., $D_2 = 0$). Assuming acceleration and braking phases of equal magnitude and time duration, Eq. 37 can be used to compute the task time.

$$T = 2\sqrt{\theta/\alpha} \tag{37}$$

For the loaded arm depicted in Figure B-8, the acceleration level, α, is taken from the curve for mode D at $\rho = 1$. Equation 37 yields for this case

$$T_L\sqrt{F_M} = 2\sqrt{\frac{\theta_S}{.0034}} \tag{38}$$

where T_L denotes the task time. Similarly, for the unloaded arm in Figure B-9,

$$T_U \sqrt{F_M} = 2\sqrt{\frac{\theta_S}{.08}} \tag{39}$$

where T_U is the task time for the unloaded arm. Equations (38) and (39) are plotted in Figure B-11. To obtain the task times corresponding to a particular value of F_M, one merely has to divide the values in Figure B-11 by the $\sqrt{F_M}$. For example, a manipulator that can exert a minimum static tip force of 10 lbs is capable of rotating the 10.27 slugs payload through an angle of 90^o in 13.6 seconds and can rotate itself (unloaded arm) through 90^o in 2.84 seconds.

It is noted that the task considered above is rather severe in that each joint must accelerate its largest moment of inertia when the arm is fully extended. For this reason, one can expect to encounter lower task times for similar maneuvers involving non-zero values of θ_E and θ_W (i.e., when the arm is not fully extended).

4. Summary

Manipulator strength can be characterized by its static or dynamic force capabilities. In general, the static and dynamic force capabilities are not the same. The differences are significant when moving payloads with masses of the same order as the manipulator mass. For the heavier payloads (i.e., payload masses greater than three times the arm mass) and for motions that do not involve payload rotations, the static and dynamic force capabilities are effectively the same.

If a manipulator is intended primarily to transport massive objects, it is reasonable to base joint torque capability on a dynamic requirement. On the other hand, if most of the manipulator tasks involve the moving and servicing of relatively light payloads, it is likely that static friction forces will present the greatest burden. When this is the case, it is advantageous to determine joint torques from a static

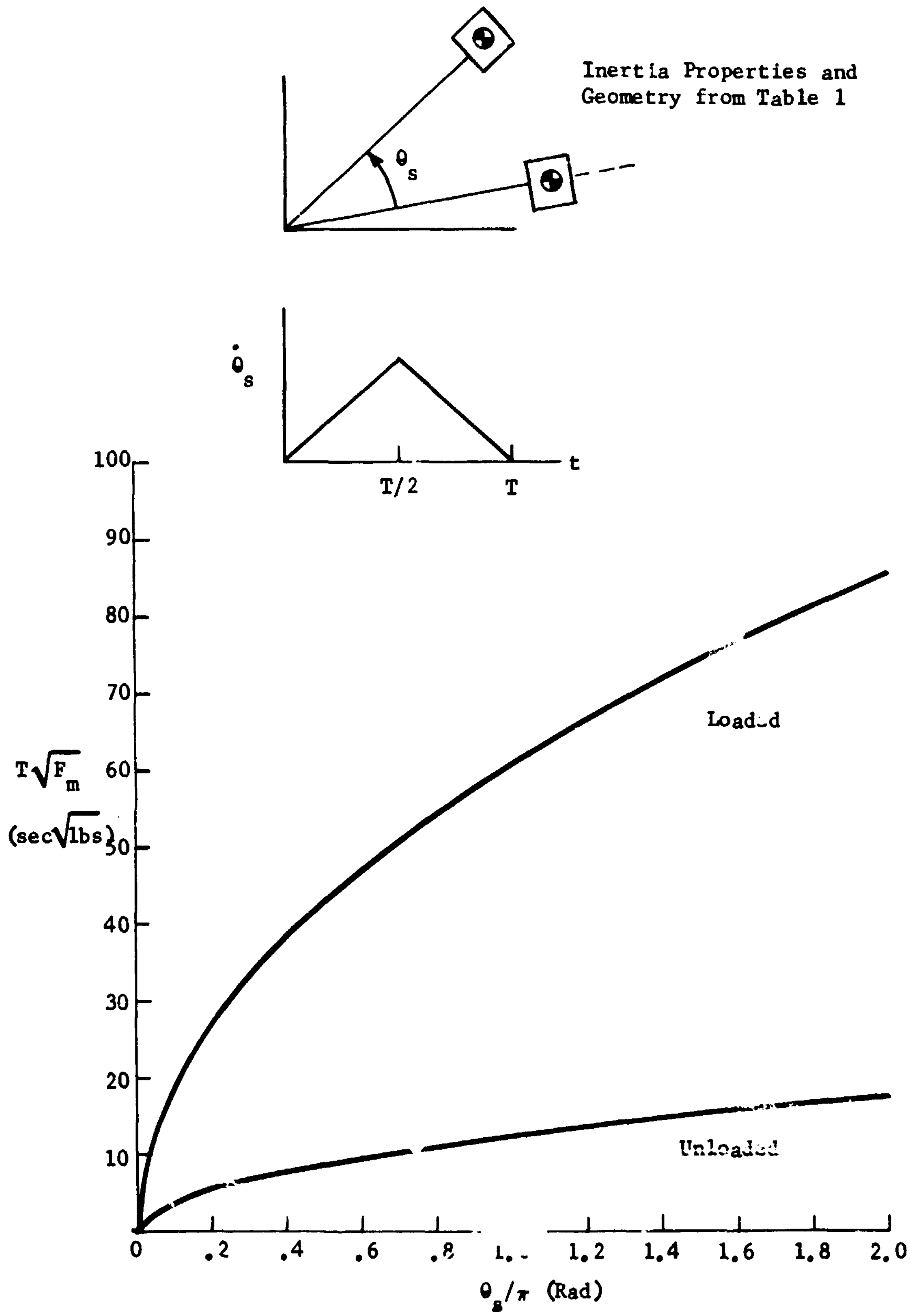


Figure B-11 Task Times for Loaded and Unloaded Manipulator force requirement and then examine the resulting dynamic capabilities to insure reasonable task times.

When the joint torques are to be determined from a static force requirement, the designer can take advantage of a characteristic shared by all articulated joint manipulators, namely the existence of a so-called "weakest" configuration. By distributing joint torques to maintain static equilibrium with a force F_M while the arm is in one of its weakest configurations, the designer is assured of a manipulator sufficiently powered to exert at least a tip force F_M (in any direction in which the tip can move) while the manipulator is in any other configuration.

Having selected joint torques corresponding to a minimum tip force F_M, one can obtain a comprehensive static force map for the manipulator. In so doing, tip positions and force directions will be encountered where force magnitudes, several times greater than F_M, are possible. Thus, by properly mounting the manipulator in its environment (or selectively arranging the environment about the manipulator), one can take advantage of the high strength regions of the arm and avoid over-designing torque motors simply because a few tasks require high static force levels.

By deriving appropriate equations of motion for the manipulator, one can investigate what dynamic capabilities are afforded by a particular choice of joint torques. Using joint angular acceleration levels as a measure of dynamic capability, it is possible to relate the dynamic character of a manipulator directly to the minimum static tip force capability.

For tasks involving payloads with a significant moment of inertia about their mass centers, the acceleration levels are limited by the outermost joint (assuming joint torques are based on static tip force).

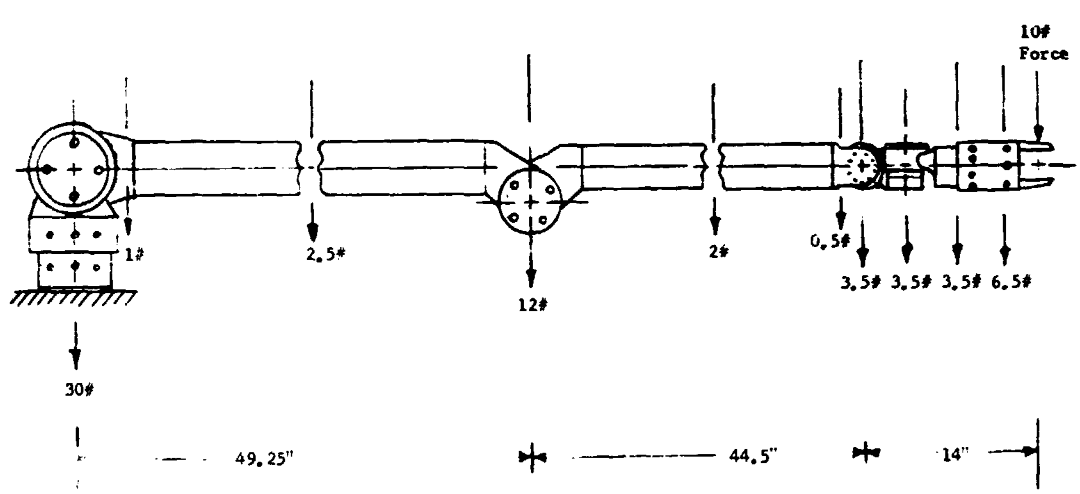
Thus, if one should find the acceleration capability of a statically desi, ,ed manipulator to be inadequate, it is worth investigating what increases can be obtained by strengthening the outermost joint (as opposed to simply in·reasing the minimum static tip force and thus the torque capability of all the joints).

APPENDIX C: DEFLECTION AND VIBRATION ANALYSIS

This analysis was based upon the manipulator preliminary mass properties shown in Fig. C-1.

1. Stress Calculations

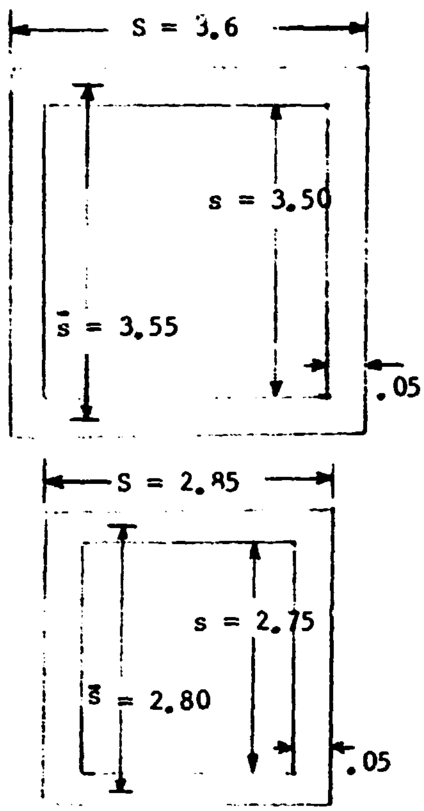
The upper arm segment from shoulder to elbow is a 4 x 4 x .25 in. [illegible] with the wall thickness reduced to 0.05 in. This section comes in 6061-T6, whereas thinner wall sections come in 6063-T52, an architectural alloy with good dimensional control, but low ductility. The lower or forearm, from elbow to wrist is a 3 x 3 x .125 in. section with the wall thickness reduced to .05. This section comes in 6061-T4. The aluminum alloy 6061 is both extrudable and weldable, and is an aircraft material, whose properties, $E = 10 \times 10^6$ psi and $\rho = 0.098$ pci, are given in MIL-HDBK-5 "Strength of Metal Aircraft Elements".



Total Weight: 63 lbs; M_{Elbow} = 907 in-lb; $M_{Shoulder}$ = 2518.5 in-lb

Figure C-1 Preliminary Mass Properties

The properties of these sections are shown in Fig. C-2 and calculated, for convenience, about an axis of symmetry.



$$I = \frac{S^4 - s^4}{12} = \frac{3.60^4 - 3.50^4}{12} = 1.491592 \text{ in}^4$$

$$\bar{I} \approx \frac{2}{3}\bar{s}^3 t = \frac{2}{3} x 3.55^3 x .05 = 1.491296 \text{ in}^4$$

$$A = S^2 - s^2 = 3.60^2 - 3.50^2 = .71 \text{ in}^2$$

$$\bar{A} = 4\,\bar{s}\,t = 4 x 3.55 x .05 = .71 \text{ in}^2$$

$$I = \frac{S^4 - s^4}{12} = \frac{2.85^4 - 2.75^4}{12} = .731967 \text{ in}^4$$

$$\bar{I} \approx \frac{2}{3}\bar{s}^3 t = \frac{2}{3} x 2.80^3 x .05 = .731733 \text{ in}^4$$

$$A = S^2 - s^2 = 2.85^2 - 2.75^2 = .560 \text{ in}^2$$

$$\bar{A} = 4\,\bar{s}\,t = 4 x 2.80 x .05 = .560 \text{ in}^2$$

Figure C-2 Segment Sectional Properties

The critical stress condition is flat plate buckling under compression due to bending. From Roark, Table XVI, Case A3

$$F_b = 5.73 \frac{E}{1 - \nu^2} \left(\frac{t}{S}\right)^2$$

$$= 5.73 \left(\frac{10^7}{.91}\right)\left(\frac{.05}{3.55}\right)^2 = 12491 \text{ psi for 4"}$$

$$= 5.73 \left(\frac{10^7}{.91}\right)\left(\frac{.05}{2.80}\right)^2 = 20079 \text{ psi for 3"}$$

F_{cy} = 14,000 psi for T4 $\quad$ F_{ty} = 16,000 psi for T4

= 34,000 psi for T6 $\quad$ = 35,000 psi for T6

Consider the unloaded arm fully extended in one 'g'. From Fig. C-1, the bending moments at the elbow and shoulder are:

$$M_E = 907 \text{ in lb}$$

$$M_s = 2518.5 \text{ in lb}$$

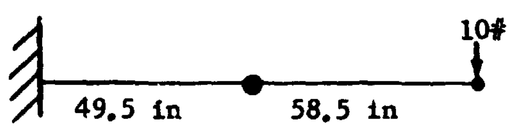
The flat plate compressive stress are:

$$\sigma_E = \frac{907 \times 1.43}{.731967} = 1772 \text{ psi } (< 20079 \text{ psi})$$

$$\sigma_s = \frac{2518.5 \times 1.8}{1.491592} = 3039 \text{ psi } (< 12491 \text{ psi})$$

Under a 45° roll of the arm, the corners would see these stresses increased by $\sqrt{2}$ but buckling is not critical and the stresses are still low.

Under a 10# design tip load the elbow and shoulder bending moments are:



$$M_E = 585 \text{ in lb}$$

$$M_s = 1080 \text{ in lb}$$

The resulting maximum stresses are:

$$\sigma_E = \frac{585 \times 1.43 \times \sqrt{2}}{.731967} = 1616 \text{ psi } (< 34{,}000 \text{ psi})$$

$$\sigma_s = \frac{1080 \times 1.8 \times \sqrt{2}}{1.491592} = 1843 \text{ psi } (< 14{,}000 \text{ psi})$$

Thus, the unloaded arm could support its own weight in one 'g' and is not stress-critical under a 10# tip load, at least as far as the tube sections are concerned. The most critical area is a flat side in compression near the shoulder.

2. Static Deflection

The static deflection δ_{ST} of the tip of the unload arm under one 'g' is a measure of the ratio of the spring mass to the stiffness of the spring and is used to calculate natural frequencies.

The weight data have been simplified slightly, assuming all weights are applied at the joints, including the tip. The bending moment diagram shown in Fig. C-3, has the correct values at the joints and is in effect linearized between joints. The error is slight.

The resulting deflection is given by:

$$\delta_{ST} \times 10^6 = \frac{58.5^2 \times 123.913}{3} + \frac{49.5 \times 108.0385}{2 \times 91.5} \times 49.5 \times 60.8075 \times 83.25$$

$$= 141354 + 244667 + 250580$$

$$\delta_{ST} = .6366 \text{ in}$$

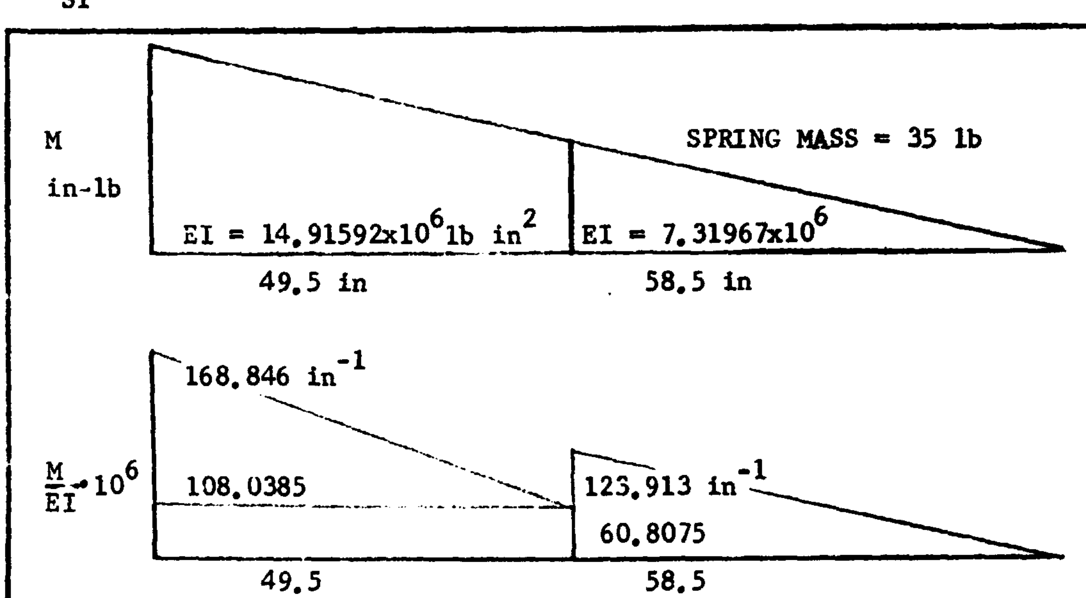


Figure C-3 One-g Bending Moment Diagram

The deflection due solely to a 10 lb tip force, with reference to Fig. C-4, is given by:

$$\delta_{ST} \times 10^6 = \frac{79.9216 \times 58.5^2}{3} \times \frac{33.186 \times 49.5}{2 \times 91.5} + 39.2198 \times 49.5 \times 83.25$$

$$= 91171 + 75154 + 161620$$

$$\delta_{ST} = .3279 \text{ in.}$$

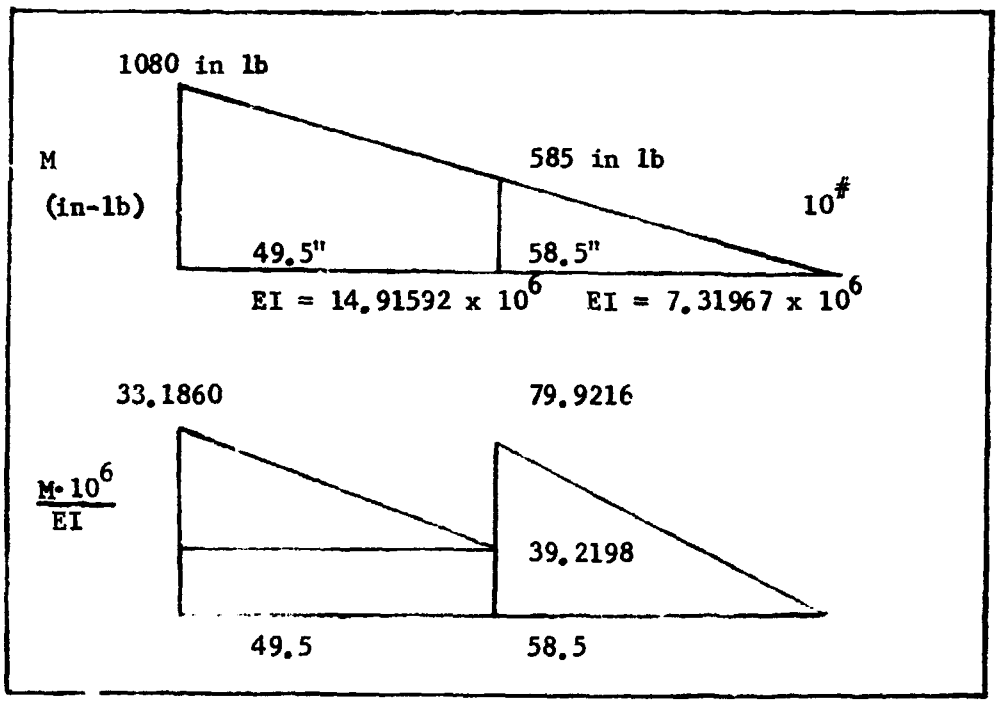
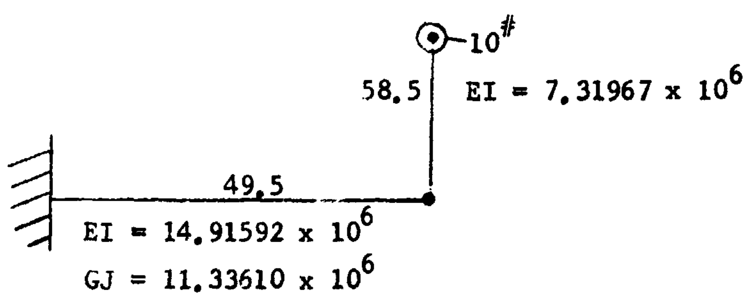


Figure C-4 Tip Force Bending Moment Diagrams

It is of interest to consider the possible deflection of the arm in a 90° bent configuration, with a 10 lb tip load.



$J = 2I$

$G = .38E$

$GJ = .76EI$

Each arm section bends under the 10 lb load, independently. In addition the upper arm twists, rotating the lower, producing tip deflection

$$\theta = \frac{T}{GJ} = \frac{10 \times 58.5 \times 49.5}{11.33610 \times 10^{6}}$$

$$\delta_{\theta} = 58.5\theta = \frac{10 \times 58.5^{2} \times 49.5}{11.33610 \times 10^{6}} = 149435 \times 10^{-6}$$

$$\delta_{U} = \frac{P\;^{3}}{3EI} = \frac{10 \times 49.5^{3}}{3 \cdot 14.91592 \times 10^{6}} = 27104 \times 10^{-6}$$

$$\delta_{L} = \frac{P\;^{3}}{3EI} = \frac{10 \times 58.5^{3}}{3 \cdot 7.31967 \times 10^{6}} = \underline{91171 \times 10^{-6}}$$

$$\sum \delta = .2677 \text{ inch}$$

This is slightly less than $\delta = .3279$ for the straight arm.

3. Natural Frequencies

For a uniform beam, about 24% of the weight of the beam should be added to the tip mass to account for the effect of the beam mass on the fundamental frequency. However, this beam is heavier in proportion to its stiffness in the forearm section and it is appropriate to assume more than 24%, say enough to produce the static deflection of the unloaded beam, to the tip mass. This mass is 0.6366/0.3279 x 10 = 19.4 lb.

Based upon the arm loaded with a 300 lb mass,

$$\delta_{ST} = \frac{319.4}{10} \times .3279 = 10.47 \text{ in.}$$

The natural frequencies of the extended arm, both loaded and unloaded are:

$$f_n = \frac{1}{2\pi}\sqrt{g/\delta_{ST}} = \frac{1}{2\pi}\sqrt{\frac{386}{10.47}} = .97 \text{ hz. for the loaded beam}$$

$$f_n = \frac{1}{2\pi}\sqrt{g/\delta_{ST}} = \frac{1}{2\pi}\sqrt{\frac{386}{.6366}} = 3.9 \text{ hz. for the unloaded beam}$$

The frequency of operator command inputs is estimated to be 3 hz maximum. It is normally desirable to have the natural frequency of a system be at least twice the frequency of any input disturbance, so that the disturbing force is spread over several cycles of the vibrating system and is thus out of phase with it about as long as in phase, and the net energy pumped into the system is small. When the frequencies are equal, the input force is always pushing the system in the direction it is moving so maximum energy is pumped into the system and the displacement increases to such large values that the system may be damaged.

In order that the operator commands should first, not excite resonance, and second, appear to the system as steady forces, the natural frequency of the system should be say, 6 hz which means that the arm must be $(\frac{6}{.97})^2$ or about 39 times as stiff as shown.

Since for a given maximum dimension, and equal weight,the square section is already optimum, only three alternatives exist. A stiffer material may be used; the diameter may be increased; and the wall thickness may be increased. A high modulus composite such as boron or graphite would increase the stiffness 2 to 3 times for the same weight. For other metals, except berillium,stiffness is about proportional to weight. A change of wall thickness produces weight increase proportional to stiffness increase also. The most efficient way is to increase the diameter since stiffness goes up as the cube and weight as the first power. All of these are unattractive ways to produce a factor of 39.

However, the manipulator arm has some characteristics which modify its behavior as compared to a simple spring-mass system. If the tip force exceeds some nominal value, some or all joints will backdrive, absorbing energy. For example, if the tip deflection exceeds .3279 inch which corresponds to a 10 lb tip force, this will produce bending moments at the joints exceeding their respective backdrive torques and they will absorb the excess kinetic energy of the vibrating mass, reducing overswing on the next half cycle.

Thus, inadvertent resonant operator input cannot damage the system, and the maximum displacement of the tip should not exceed .3279 inch from nominal.

Based upon these considerations, it is recommended that further dynamic analyses of the total system, including the bending response of the arm, be conducted in the future.

APPENDIX D: PRELIMINARY SPECIFICATION FOR MANIPULATOR SYSTEM

Introduction

A Preliminary Manipulator System Specification has been prepared as a preview of the typical Specification format and information required to design and build a "zero-g" operable manipulator. The specific Manipulator Specification format for a flight unit will be dependent on the specification boilerplate defined by the Contractor End Item Specification (CEI). The CEI could call out the manipulator as either the end item or a subassembly to a final end item such as a Free-Flying Spacecraft.

The Preliminary Manipulator Specification is prepared with the primary objective of providing the manipulator designer the necessary program and system constraints needed to propose and cost a specific design. The requirements presented first refer to mission objectives followed by the implications that influence system design. Basic reference material will be taken from existing Government material relating to Shuttle Program Accommodations.

DRAWING NO.

Table of Contents

DRAWN BY	DEPT	DATE	MARTIN MARIETTA CORPORATION DENVER DIVISION P.O. BOX 179 DENVER, COLORADO 80201
CHECKING			
GROUP ENGR	SIGNATURE REQD		(Preliminary) EQUIPMENT SPECIFICATION MANIPULATOR ASSEMBLY REMOTELY OPERATED SYSTEM
STRESS			
WEIGHT		(A/B)	
CUSTOMER RPRSNTV			
PROGRAM RPRSNTV	SIGNATURE REQD		SIZE A · CODE IDENT NO. 04236 · XXXXXX · PART NO. PROM
			SCALE · PAGE D-2 · SHEET OF XX

1.0 SCOPE

1.1 General - This specification covers the preliminary design, performance and testing requirements for a man-tended, zero gravity, manipulator system. Hereinafter referred to as the manipulator assembly.

1.2 Intended Use - The manipulator assembly is intended for use in the Shuttle Transportation System (STS) on such vehicles as Tug, Shuttle payloads and a remotely controlled Free Flying Teleoperator type spacecraft. The manipulator assembly provides the extension of man's capabilities in space through the remotely controlled device designed to augment man's sensory, manipulative and cognitive skills.

2.0 APPLICABLE DOCUMENTS

Listing of the existing NASA, Federal, Military and Contractor specifications which may be utilized in the design, fabrication, testing and administration of the project where practicable.

3.0 REQUIREMENTS

3.1 Mission Objectives - The baseline mission for the manipulator is to remove, replace modules on an orbiting satellite within a distance of 5000 m (16,500 ft) of a Shuttle Orbiter. The manipulator is also baselined to be a general purpose space tool attached to a Free Flying Teleoperator System (FFTS). It is also assumed that the manipulator will not be activated for operation until the FFTS has d[illegible]ed with the space vehicle to be serviced and rigid attachment has been confirmed. The tasks now assigned to the manipulator are:

- Tether vehicles if required
- Open hatch and make visual inspection
- Remove module from satellite
  - Release module attachment fasteners
  - Break line connectors (electrical and fluid)
- Module translation and stowage
  - Insert and lock attachment fasteners
- Replace module on satellite
  - Insert and lock attachment fasteners
  - Make line connections

The system will be capable of repeating this work sequence for 50 times during a seven day mission.

3.2 STS Mission Constraints - Selected Shuttle program spacecraft requirements which may impose design restrictions onto an FFTS manipulator development are discussed in the following paragraphs. The requirements as presented are not intended to provide all the FFTS manipulator system requirements, but those related to remote manipulator needs derived from Shuttle mission objectives and their implication on development costs, crew safety, operating time/complexity and high probability of mission success.

3.2.1 Shuttle Orbiter Constraints - When operational, the Shuttle Orbiter will o[illegible]ate as a common carrier providing the launch, orbit, and return capabilities to essentially anyone who can provide the necessary justification to receive a flight assignment. With the variety of potential users, a system of considerable flexibility is required. As the flexibility increases so does the need for system standardization and cost effectiveness. One of the methods identified by NASA studies, to increase cost effectiveness, is the use of manipulators as Shuttle payload support devices. The manipulator device of primary interest is a general purpose type that would be attached to a Free Flying Teleoperator System (FFTS).

3.2.1.1 Functional Considerations - The Shuttle Orbiter will be capable of providing the following functions:

(a) A mounting and stowage location will be provided within the confines of the Shuttle payload bay.

(b) A mechanical device will be provided by the Shuttle Orbiter to remove and deploy the FFTS from its mounting and stowage location and to capture and replace it within the bay.

(c) A FFTS Control and Display Station will be provided within a pressurized portion of the Shuttle spacecraft. The station will provide a command and telemetry link to the FFTS.

(d) A commodity resupply station will be provided with the following capabilities:

1. Power: Voltage - 24 to 30.5 VDC continuous
Supply Continuous - 1 Kw average, 1.5 Kw peak
Supply Special (Max) - 3 Kw average, 6 Kw peak
Quantity - 50 Kw (total for payloads)

2. Propellant transfer: TBD

3. Film transfer: TBD

3.2.1.2 Physical Characteristics - The FFTS will be compatible with the following Shuttle Orbiter payload bay characteristics:

(a) The Shuttle payload bay can stow a combined payload that does not exceed the following dimensions:

1. Length - 18.3 m (60 ft)

2. Width - 4.57 m (15 ft)

3. Height (closed) - 4.57 m (15 ft)

4. Volume - (Rectangle) - 180.0 cu m ($6360\ ft^3$)
(Cylinder) - 300.0 cu m ($10600\ ft^3$)

(b) Typical payload mounting locations within the Shuttle bay are defined in JSC 07700 Volume XIV, Rev B.

3.2.1.3 Environments - The manipulator assembly will perform during and after exposure to the following environments and ranges.

(a) Vibration, Acoustic and Shock - These values to be provided later.

(b) Payload Bay Atmosphere - Conditioned air will be supplied to the payload bay at the launch pad up to 30 minutes prior to propellant loading. At that time, GN_2 will be supplied up to lift-off. Purge capability is as follows:

1. Flow rate - 0 to 90 Kg/Min (0 to 200 lb/min)

2. Temperature - range of 45°F to 120°F controlled to ± 2°F of desired setting

3. Cleanliness - class 100,000, see Federal Standard 209A

4. Humidity, Air - 0 to 43 grains/pound of dry air
   Humidity, GN_2 - 0 to 1 grains/pound of dry air

(c) Launch Atmosphere - The payload bay is vented during launch and entry phases and unpressurized during the orbital phase of the mission.

(d) Temperatures - The payload temperature and temperature environments the payload will experience in the payload bay requires a detailed analysis of the boost through entry, vehicle design and orientations. The following requirements will be assumed for the orbiter thermal design.

The internal wall temperature limits for the payload bay, not considering payload heat addition or removal, will be within the following ranges:

Condition	Minimum	Maximum
Prelaunch	+ 40°F	+ 120°F
Launch	+ 40°F	+ 150°F
On-Orbit (doors closed)	See C & D	See A & B
(doors open)	TBD	TBD
Entry and Post Landing	- 100°F	+ 200°F

A. Total bay heat gain; average 0 Btu/ft^2-hr

B. Heat gain, local area 3 Btu/ft^2-hr

C. Total bay heat loss average 3 Btu/ft^2-hr

D. Heat loss, local area 4 Btu/ft^2-hr

Throughout on-orbit operations, the radiator/payload doors will normally remain open for radiator heat rejection to space. Exposure of the payloads to space environments requires each payload to provide its own passive and/or active thermal control to aid that available from the orbiter.

3.2.2 Shuttle Payload Constraints - The term Shuttle Payloads is a collective phrase used to describe the operating entities that are proposed for space launching. It includes the mission experiments, associated spacecraft and supporting subsystems, but excludes launch vehicle and related elements such as the adapter or the fairings that are not functional on-orbit. Payloads in all disciplines are involved: Astronomy, Chemistry and Physics, Communications and Navigation, Earth Observations, Material Processing, Space Technology and Life Sciences. To provide a payload support function with the FFTS requires a dual interface role in which the remote manipulator type vehicle must have a docking capability with both the Shuttle orbiter and Shuttle payloads. This specific application shows up in the current Shuttle mission plans. During the first two years of orbital operation, the FFTS has been identified as the space tool for deploying and retrieving the Bio-Experiment Satellite and for retrieving the Long Duration Exposure Facility spacecraft. Along with the deployment and retrieval activities other areas have been identified that can contribute significantly to the Shuttle program.

3.2.2.1 Functional Considerations - Analysis of Shuttle missions indicates that the FFTS can contribute significantly in a support capacity to Shuttle program objectives in five broad areas; payload deployment, payload inspection, payload retrieval, payload servicing and EVA assistance.

(a) Various payloads such as the Bio-Experiment Satellite (BES) requires spinup of 5.65 rad/sec prior to release in the proper orbital position.

(b) Satellite spinup capability will be provided from 0 to 1 rev/sec (2πrad/sec).

3.2.2.2 Payload Characteristics - The mass, dimensions, orbits and flight dynamics for Shuttle payloads play an important part in establishing FFTS and manipulator capabilities. With so many varieties of payloads being considered in the present time period, it has been necessary to focus on a representative cross section of payloads from the NASA payload model (Ref. 3). This was done in a previous contract NAS8-29904, (Ref. 4) which identified four payloads covering a wide range of characteristics: Large Space Telescope (LST), Long-Duration Exposure Facility (LDEF), Earth Observatory Satellites (EOS), and Bio-Experiment Satellite (BES). The basic satellite characteristics baselined for this study are presented in Table 3-1.

Table 3-1 Reference Satellite Characteristics

Satellites*		Weight Kg(lb)	Length m(ft)	Diam. m(ft)	I_{xx} Kg-M^2 (slug-ft^2)	I_{zz} Kg-M^2 (slug-ft^2)
Large Space Telescope		9400(207000)	13(42)	4.3(14)	21,400 (15,750)	142,300 (104,700)
Long Duration Exposure Facility		3800(8500)	9.2(30)	4.3(14)	8790 (6460)	31,250 (23,000)
Earth Observatory Satellites	EO-1	900(2000)	3.7(12)	1.5(5)	1280 (944)	4060 (2990)
	EO-2	900(2000)	3.7(12)	1.5(5)		
	EO-3	1700(3800)	4.9(16)	2.4(8)		
	EO-4	180(400)	2.1(7)	1(3.05)		
	EO-6	1140(2500)	4.3(14)	3.3(11)		
Bio-Experiment Satellite		180(400)	2(6.8)	1(3)	1896 (1397)	74.5 (54.8)

* "Baseline" FFTS Experiments

3.2.3 Shuttle FFTS Constraints - The baseline vehicle selected for which the manipulator will be attached is the Free Flying Teleoperator System. This system is envisioned as an assemblage of elements operating, cooperatively, under the control supervision of a human operator located away from the actual performance location. The subsystems making up this assemblage are modularized to be added or deleted as mission functions dictate. These modules are integrated into an autonomous system with certain automatic, augmentative features. All automatic features would be under the supervisory control authority of the operator and have a manual override feature. The modules considered for a complete FFTS system fall into related groups, or subsystem categories. The subsystem categorizations to be used are as follows:

- Manipulators
- Docking Device
- Visual/Specialized Sensors
- Guidance/Navigation/Control
- Specialized Computation
- Propulsion/Reaction Control
- Power
- Central Data Relay Net
- Communication and Data Management
- Safety, Caution/Warning
- Command, Control and Display Station

The FFTS system will be designed for a total life of 10 years and the operational time of the equipment will be 500 hours. The flight FFTS will be capable of being returned to Earth in the Shuttle and reused with a minimum of maintenance and ground turnaround time.

The flight FFTS must withstand environments induced during ground operations, boost and landing (including ascent, abort, crash landing) while in the Shuttle cargo bay, and orbital operations including dynamic acceleration, pressure, sound energy, contaminations, vibration, shock, temperature and humidity.

As a part of the system, the FFTS will have a station that can be mounted in the Shuttle cargo bay. The station will be used as a berthing port for the FFTS, when it is not in operational use; a structural mount for holding the FFTS during Shuttle liftoff, orbital insertion, deorbit, and reentry, and landing (including ascent abort crash landing); a checkout station; and for on-orbit refueling.

The FFTS will be capable of being inserted and removed from the Shuttle cargo bay while the Shuttle is in a vertical position on the launch pad, or when the Shuttle orbiter is horizontal on Earth.

3.2.3.1 Functional Characteristics - The FFTS is considered a Shuttle payload with a complimentary requirement to provide operational support to other Shuttle payloads. The FFTS will be transportable into orbit by the Shuttle orbiter and be remotely controlled from the Shuttle, Sortie Lab and/or ground. As an operational space tool the FFTS will be capable of the following functions:

(a) Removing and replacing modules from satellites and space stations external to the Shuttle

(b) Certain payload servicing by transporting replaceables and expendables to satellites, and accomplishing servicing

(c) Providing a degree of mobility to serve as a camera carrier for increased visual documentation of space activities, or for the deployment of experimental support equipment

(d) Obtaining live replacement modules or other equipment from, or delivering spent modules and equipment to, the Shuttle Attached Manipulator System for retrieval from or stowage in the cargo bay

3.2.3.2 Physical Interfaces - The FFTS spacecraft baseline is defined in (Ref. 1) and summarized as follows:

Envelope dimensions; 0.9 x 0.9 x 0.9 m (3 x 3 x 5 ft)

Estimated weight; 185 kg (402 lbm)

Commodity loading; Fuel and High Pressure Gas

Stowage Attachments; TBD

Subsystem removal; Modular Design

3.2.3.3 General System Requirements - The following requirements apply equally to all FFTS subsystems and, therefore, are considered system level requirements for a fully operational FFTS.

3.2.3.3.1 FFTS Removal/Insertion on Shuttle Orbiter - The FFTS will be compatible with the Shuttle Attached Manipulator System for on-orbit insertion and removal from the cargo bay. For capture by Shuttle Attached Manipulator System, the FFTS must maintain the following attitude and residual velocities:

Longitudinal velocity; 0.015 m/sec (0.05 ft/sec)

Lateral velocity; 0.015 m/sec (0.05 ft/sec)

Angular misalignment; $\pm$ 0.009 rad ($\pm$ 0.5 deg)

Angular rate; 0.0175 rad/sec (1 deg/sec) maximum

3.2.3.3.2 FFTS Maneuverability - The FFTS will be the active element in satellite acquisition, rendezvous, and capture procedures. The FFTS thrust program will deliver the cargo to the desired location within an accuracy of $\pm$ 1.852 km ($\pm$ 1 n mi) 3σ.

The FFTS will be capable of rendezvous and capture of a target object the position of which is known to $\pm$ 1.852 km ($\pm$ 1 n mi) 3σ in each axis.

The FFTS must be able to follow specified trajectories to within 5% or 0.5 m (1.6 ft).

The FFTS will maintain position and attitude rates within limits such that satellite motions can be arrested within 300 seconds.

3.2.3.3.3 FFTS Mass Transportability - The FFTS will have the capability to transport the following sizes and masses to required destinations and return the unloaded FFTS to the Shuttle.

		Minimum	Maximum
Size:	Length, m (ft)	-	3.43 (11)
	Width, m (ft)	-	2.31 (7)
	Depth, m (ft)	-	2.31 (7)
Mass:	kg (lb)		300 (660)
Transportation distance, m (ft)		200 (640)	5000 (16,500)
Time limit, sec		3600	72,000

3.3 Manipulator Performance Requirements

3.3.1 General - The manipulator assembly motion generation is provided by an operator commanded input to various electro-mechanical joint actuators. The manipulator assembly joint configuration shall provide six-degrees-of-freedom to the end effector as follows:

(a) Shoulder: Yaw and Pitch

(b) Elbow: Pitch

(c) Wrist: Pitch, Yaw and Roll

A seventh degree-of-freedom shall provide the end effector grip force.

3.3.2 Functional Characteristics - The functional characteristics of the manipulator assembly shall be as specified in the subparagraphs herein.

3.3.2.1 Manipulator Subsystems - The manipulator assembly has been categorized into four basic areas: structure, actuators, end effector and control elements.

3.3.2.1.1 Structure - The manipulator assembly shall consist of two major segments of approximately equal lengths with square cross sections and a .127/.152 cm (.05/.06 in) typical wall thickness.

(a) Reach - Working reach shall be from 30 cm (1 ft) minimum to 244 cm (8 ft) , measured along a line from the shoulder pitch axis to the wrist pitch axis. Index motions shall extend coverage to approach a hemispherical shape over the docking interface.

(b) Interchangeability - Interchangeable interfaces shall be provided between the manipulator assembly/Free Flying Spacecraft and end effector/wrist roll joint.

(c) Stowage - Stowage provision shall be provided by the compact folding back on itself at the elbow.

3.3.2.1.2 Actuators - The manipulator assembly, shall use electromechanical actuators at each joint. The basic actuator consists of motor, gear train, feedback device, (tachometer, potentiometer) and a brake. The actuators shall be designed to the following performance requirements:

(a) Travel - The manipulator assembly shall provide stops at each joint to permit the maximum travel as follows:

Shoulder:	Yaw	$\pm$ 3.5 rad ($\pm$ 200 deg)
	Pitch	3.2 rad (180 deg)
Elbow:	Pitch	3.2 rad (180 deg)
Wrist:	Pitch	$\geq$ 1.6 rad ($\geq$ 90 deg)
	Yaw	$\pm$ 1.5 rad ($\pm$ 85 deg)
	Roll	Continuous

(b) Velocities - Both loaded and no load velocities shall be controlled to the maximum as follows:

Elbow:	Pitch	0.4 rad/sec (23 deg/sec)
All Others:		0.2 rad/sec (11.5 deg/sec)

(c) Applied Torques:

Shoulder:	Yaw	123 N-m (90 ft-lb)
	Pitch	123 N-m (90 ft-lb)
Elbow:	Pitch	68 N-m (50 ft-lb)
Wrist:	Pitch	20.5 N-m (15 ft-lb)
	Yaw	20.5 N-m (15 ft-lb)
	Roll	20.5 N-m (15 ft-lb)

(d) Tip Forces:

Tip X, Y, Z	44.5 N (10 lb)
Crip	44.5-89 N (10-20 lb)

(e) Accelerations: Acceleration capability of the different manipulator joints from zero velocity to maximum velocity of 0.2 rad/sec shall be a controlled variable as a function of the applied torque.

(f) Braking: Brakes shall be provided on each joint actuator with a no slip hold capability up to the values specified in paragraph 3.3.2.1.2.c. Brakes shall be selected to provide full braking capability with power off and minimum power for disengaged brake.

(g) Backdriveability: The design or selection of rotating components which make up the actuator assembly shall incorporate low inertia design characteristics. This provides ease in backdriving, low stating torque and quick response.

(h) Duty Cycle: Each actuator shall be capable of applying the rated running torque for at least 30 seconds without exceeding a motor rotor temperature of 200°C.

3.3.2.3 <u>End Effectors</u> - The end effector of the manipulator assembly shall be a parallel-jaw type. Serrated design shall be incorporated into the jaws surface to provide slip resistance. Recesses in the jaw faces shall provide restraint and pivot points for special purpose tools.

(a) Grip Distance - The end effector jaw grip width shall be at least 7.6 cm (3 in).

(b) Grip Speed - The end effector jaws shall be capable of a closing and opening velocity of 5 cm/sec (2 in/sec).

(c) Grip Force - The end effector jaws shall apply a gripping force of 44.5 to 89N (10 to 20 lb).

(d) Backdriveability - The power linkage which provides the actuation to the end effector jaws shall be designed to be non-backdriveable up to an applied force of 224N (50 lb).

3.3.2.1.3 Control Elements - The manipulator assembly control system shall be designed for simplicity and reliability. The capability shall exist in case of a single failure for the manipulator to operate in a contingency mode. The control electronics and other control elements shall provide the manipulator assembly the following control functions:

(a) Control functions:

- The manipulator assembly shall have a position error in translation, anywhere in the defined work space, no greater than $\pm$ 0.003 m ($\pm$ 0.01 ft).

- The manipulator assembly shall have an orientation (rotational) error, anywhere in the defined work space, no greater than $\pm$ 0.035 rad ($\pm$ 2 deg).

- The incremental motion of the manipulator will be no greater than $\pm$ 0.003 m ($\pm$ 0.01 ft) in translation or $\pm$ 1.45×10^{-3} rad ($\pm$ 5 arc min) in attitude.

- The manipulator assembly shall permit application of a maximum threshold force of 2 N (0.45 lbf) regardless of control mode.

(b) Control Electronics - The amplifier shall be efficient and reversing, with the capability to provide motor protection from current surges and high voltages resulting from plugging or rapid reversal. Electronic modules shall be located in the manipulator assembly on suitable, temperature regulated heat sinks. Requirements for these heat sinks shall be determined by the manipulator thermal analysis. Due to the temperature range it may be advantageous to locate this unit on the Free Flyer.

(c) Temperature Control - Heat rejection from the manipulator actuators and amplifier shall be by passive conduction and radiation. Minimum temperature in the manipulator shall be -100°C, while maximum motor rotor temperature shall be limited to 200°C. The manipulator can be continuously in the sun, in the vehicle's shadow, or in the earth's shadow. Temperature sensors shall be provided as required for monitoring the specified limits.

(d) Feedback Devices - The selection of a Rate-Rate Control Scheme, requires that all actuators shall be provided with both tachometers and potentiometers. Command and feedback signal processing, transmission, and decoding shall be provided by a separate communication system. Individual control signals for the manipulator shall be analog.

3.3.2.2 Manipulator Support Systems - Generally the manipulator system requires a number of support systems. Some of the more important one's include the controller, the control computer, and the control and display station. These subsystems shall include but not be limited to, the functional characteristics specified herein.

3.3.2.2.1 Controller - The manipulator assembly motion control shall be provided at a remote control station; rate type hand controllers recommended are the Apollo rate type controllers. The required six-degree-of-freedom control shall be provided by two of these 3 degree-of-freedom type controllers: One a T-bar handle translation controller and the other a pistol grip attitude controller.

The controls shall be designed to permit the manipulator assembly operator with the capability to:

(a) Manipulator position increment in any axis $\pm$ 0.003 m ($\pm$ 0.01 ft).

(b) Manipulator rate (linear) 0.55 m/sec (1.8 ft/sec) maximum.

(c) Manipulator attitude $\pm 1.45 \times 10^{-3}$ rad ($\pm$ 5 arc min) increment per joint.

(d) Manipulator attitude rate 0.2 rad/sec (11.5 deg/sec) maximum.

3.3.2.2.2 Control Computer - The computation system shall contain the necessary algorithms, sequences, memory, instructions and processing required to expedite operations controlling the manipulator assembly.

(a) A supervisory override capability shall be maintained by the FFTS control station operator.

(b) The computer routines shall be adaptable and flexible allowing direct access and modification by the FFTS operator.

(c) Computational requirements needed for word memory in the rate control scheme shall be less than TBD words.

(d) Computational cycle time shall be 0.017 sec or less.

3.3.2.2.3 Control and Display Station - The manipulator assembly control and display functions shall provide the capability for an operator to input, monitor results, and change parameters to more accurately and quickly control arm motions to desired locations or targets. These C&D functions shall be integrated with C&D elements associated with the manipulator assembly carrier vehicle control. The integration procedure shall include man/machine design considerations for optimal location of displays, controls, lighting and work station. The hardware selection and panel layouts shall be applicable to the control and display hardware characteristics specified herein.

(a) Control and Display Hardware - The following control functions and associated hardware have been identified as a minimum:

Control Functions	Associated Hardware Controls	Associated Hardware Displays
Manipulator Assembly Control	(refer to Para. 3.3.2.2.1)	6-joint force, meters 6-joint moment, meters
End Effector, Grip	1-3 position toggle open-off-close	1-grip force meter
Rate Ratio (trans. & rotation)	1-3 position toggle high-med-low	
Brakes (joints)	1-push button matrix (6-buttons on-off)	status lights integrated with matrix
Force Ratio	1-rotary pot.	
Torque Ratio	1-rotary pot.	
Hazard Avoid	Toggle switch	status light

(b) Support Display Hardware - The most critical FFTS subsystem which impacts the manipulator assembly control is the visual system. Typical television visual displays that provide the following CDS manipulator system with potential control restrictions identified are:

- The visual sensor shall provide rendition of the viewed area of sufficient quality and resolution to give the operator information to make positive control decisions.

- The axis of orientation is the X axis in conventional spacecraft coordinates.

- The field-of-view is variable from 0.122 rad (7 deg) to 0.7 rad (40 deg).

3.3.2.3 <u>Power Source</u> - Power will be provided from the Free Flying vehicle system at a voltage level of 28 $\pm$ 4 Vdc to the manipulator assembly

3.3.2.4 <u>Power Consumption</u> - The maximum power consumption of the manipulator assembly shall not exceed <u>TBD</u> watts per FFTS mission.

3.3.3 <u>Operability</u> -

3.3.3.1 <u>Reliability</u> - The manipulator assembly shall be designed to the following reliability goals <u>TBD</u>. The use of proven components and techniques should be applied to the maximum extent. It shall be a design goal that no single failure point shall adversely affect the safety of personnel or the spacecraft.

3.3.3.2 <u>Maintainability</u> -

3.3.3.2.1 <u>General Requirements</u> -

(a) The manipulator assembly shall be designed to provide accessibility, replaceability and serviceability consistent with efficient servicing, testing, and maintenance requirements. Careful consideration shall be given to the maintainability of the unit and the elimination of potential sources of human induced failures.

(b) The principles of modular construction shall be employed in designing the manipulator assembly to permit maintenance and replacement to be performed at the component level. Components expected to require servicing or maintenance shall be designed to be accessible without the removal of other components, wire bundles, or fluid lines.

3.3.3.2.2 Additional Requirements for Inflight Maintainability - Where inflight maintenance is required based on the criticality, complexity, reliability, or reactivation requirements, the following shall apply:

(a) Positive malfunction isolation to the component level shall be provided and shall minimize necessity for astronaut interpretations or reference to handbooks. Each access shall be labeled with the nomenclature of the component(s) or area accessible through it.

(b) Components shall be replaceable and adjustments possible with the use of a minimum number of tools which shall be standard tools wherever possible. The design of the manipulator assembly shall make maximum use of standard replaceable components. Components, tools, connectors and similar items shall be designed so as to facilitate one-handed operation by a suited flight crew member. Tools shall be compatible for use in the natural and induced environments as applicable.

(c) Replacement components shall be designed with visual alignment devices such as keys or pins. Blind installations shall be avoided.

3.3.3.3 Useful Life - The useful life of the manipulator assembly shall include the period from final acceptance testing through shelf life, prelaunch life, operating life and until destruction of its identity by final disposal. This total time shall be for a period of 5 years.

3.3.3.3.1 Prelaunch and Launch Life - The manipulator assembly shall meet the requirements of the specification during the exposure time of the environments of paragraphs 3.3.3.4.1 and 3.3.3.4.2.

3.3.3.3.2 Operating Lifetime - The manipulator assembly shall meet the requirements of this specification during 100 hours (per orbiting mission) of exposure to the environments of paragraph 3.3.3.4.3. The manipulator assembly shall be capable of 100 orbiting missions to the above environmental exposure.

3.3.3.4 Environments -

3.3.3.4.1 Natural Environments - The natural environments include transportation and storage. The manipulator assembly shall perform as specified herein after exposure in a non-operating condition to any combination of the following environments and ranges.

(a) Temperature: -40°F to +160°F

(b) Pressure: 500 mmHg (5 psia) to 1260 mmHg (20 psia)

(c) Humidity: TBD

(d) Etc. (Salt fog, Rain Fungus, Sand and Dust Acceleration, Shock and Vibration - as per Shuttle Program Flight and Ground System Spec).

3.3.3.4.2 Induced Environments - The manipulator assembly shall perform after exposure to the following environments and ranges of paragraph 3.2.1.3. The paragraphs of primary concern include Shuttle Orbiter launch and ascent environments.

3.3.3.4.3 Orbital Environments - The manipulator assembly shall perform during and after exposure to the following environments and ranges and to the environments of paragraphs 3.2.1.3.c and d.

(a) Temperature: -100°F to +200°F

(b) Pressure: 500 mmHg to 10^{-7} mmHg

(c) Radiation: TBD rad/day

(d) Contamination: TBD

(e) Humidity, Shock, Vibration, Acoustic - These values to be compatible with Shuttle Program.

3.3.3.5 Transportability - Where possible the manipulator assembly shall be designed to withstand handling and transportation environments without the necessity of special containers, or the necessity of monitoring critical environments to verify that design limits have not been exceeded. Where warranted, special packaging and transportation methods shall be used to provide adequate protection and control during shipment.

3.3.3.6 Human Engineering - The manipulator assembly shall be designed so that controls are readily accessible, suitably arranged, properly identified and of such size and construction as to permit convenience and ease of operation. Controlled characteristics such as sensitivity, volume and voltage, shall increase with clockwise rotation of the control as seen from the operating position. The flow rate in fluid systems controlled by hand operated valves shall increase with counterclockwise rotation of the control as seen from the operating position. The opening of doors, lens covers, and the like, shall, when effected by rotation of a control, increase with counterclockwise rotation of that control. The position of the device (doors, lens covers, and the like) shall be displayed either directly or indirectly to the flight personnel. The setting, position, or adjustment of the controls shall not be affected by vibrations, shock, or other service conditions. All controls shall operate freely, smoothly, and easily without excessive binding, play or backlash. The manipulator assembly shall comply with the design criteria of MIL-STD-1472 and MSFC-STD-267A.

3.3.3.7 Safety -

(a) The manipulator assembly shall be designed to ensure that the safety of flight and ground personnel and the prevention of hardware damage is a prime consideration. The unit shall have adequate safeguards to prevent hazardous conditions and inadvertent operation; and, normal operations, component replacement, the act of replacing components, malfunctions, or failures shall not disable other equipment, personnel, or the flight vehicle.

(b) The design and construction of the manipulator assembly shall be such that ground or flight personnel required to handle, maintain or operate it will not be subject to injury. Sharp edges and corners, burrs, and protuberancies are not permitted. The manipulator assembly shall be designed to prevent personnel contact with high temperature surfaces and hazardous electrical points.

3.4 Design Requirements

3.4.1 General Design Features - The manipulator assembly shall consist of six-degrees-of-freedom plus a gripping capability on a general purpose manipulative device. The elements used to provide this capability shall be assembled according to the dimensions specified herein. Performance requirements for the manipulator elements shall be as specified in paragraphs 3.3.2.1 and 3.3.2.2.

3.4.1.1 Size and Configuration - The size and configuration shall be in accordance with the information presented in Fig. 1.

3.4.1.2 Weight - The manipulator assembly attached to the FFTS shall be designed to a minimum weight but shall not exceed 34 Kg (75 lb).

3.4.1.3 Thermal Characteristics - The manipulator assembly shall be designed so that thermal interchange with its potential heat sinks can be

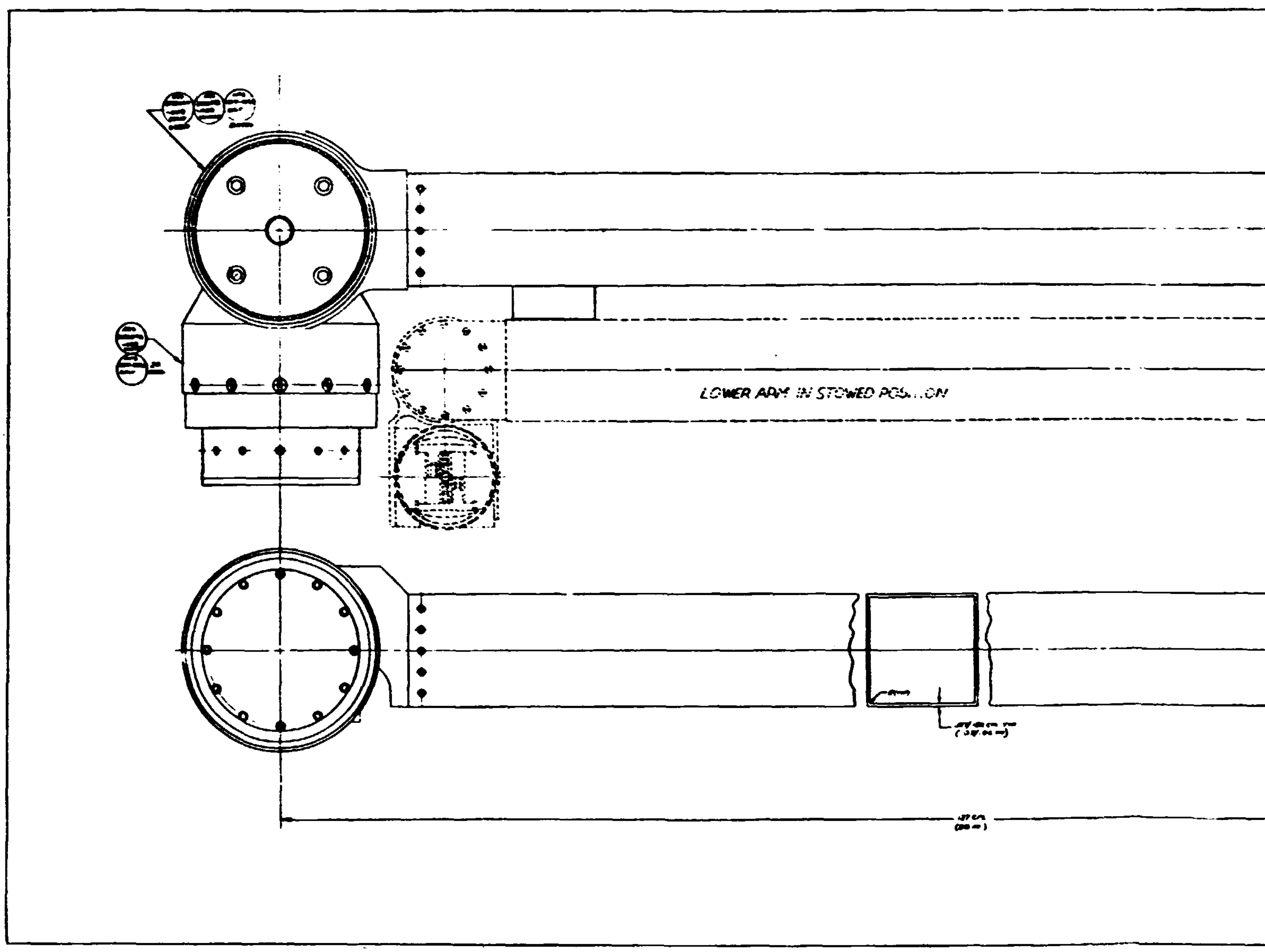


Figure 1 Manipulator System Schematic

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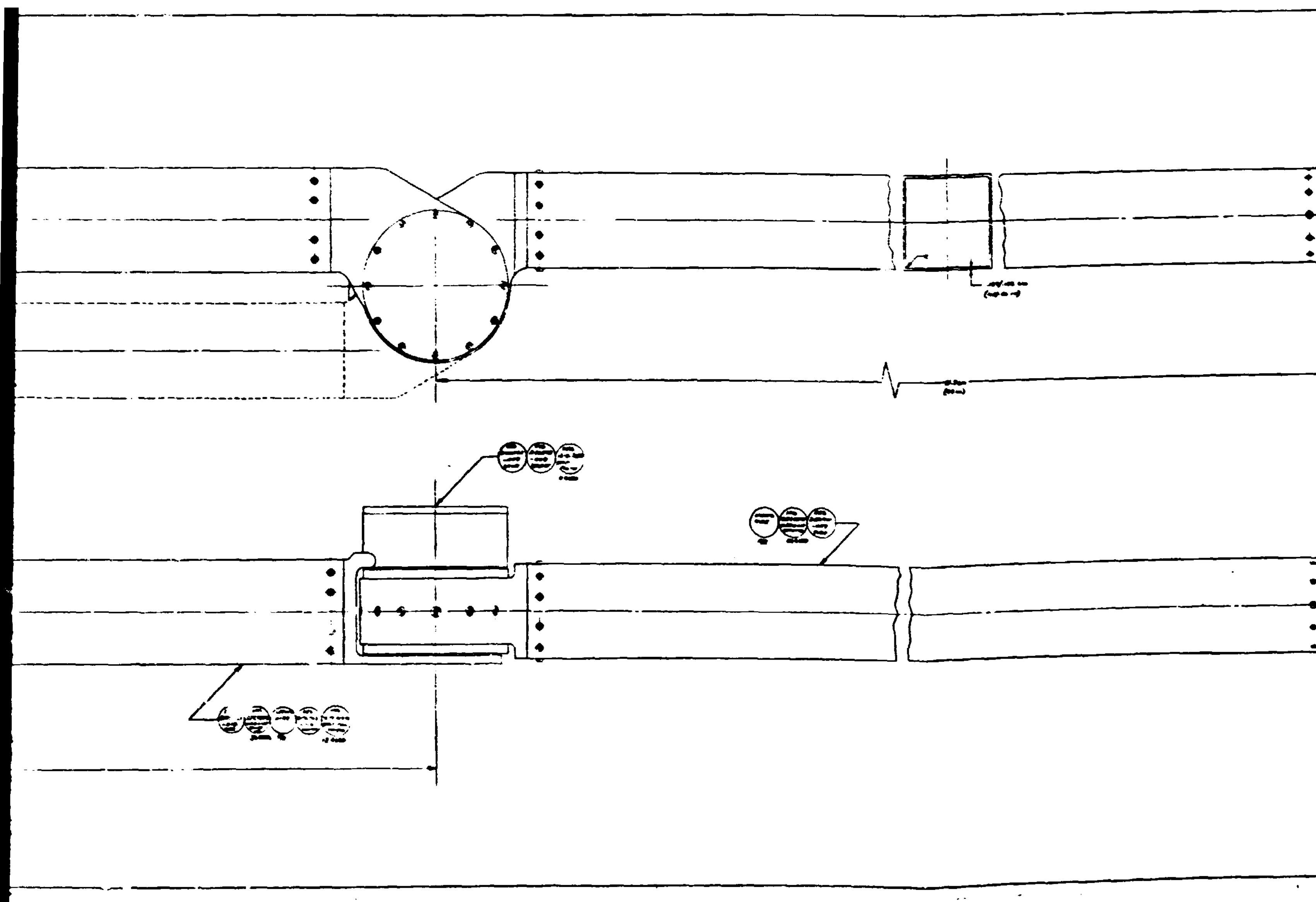

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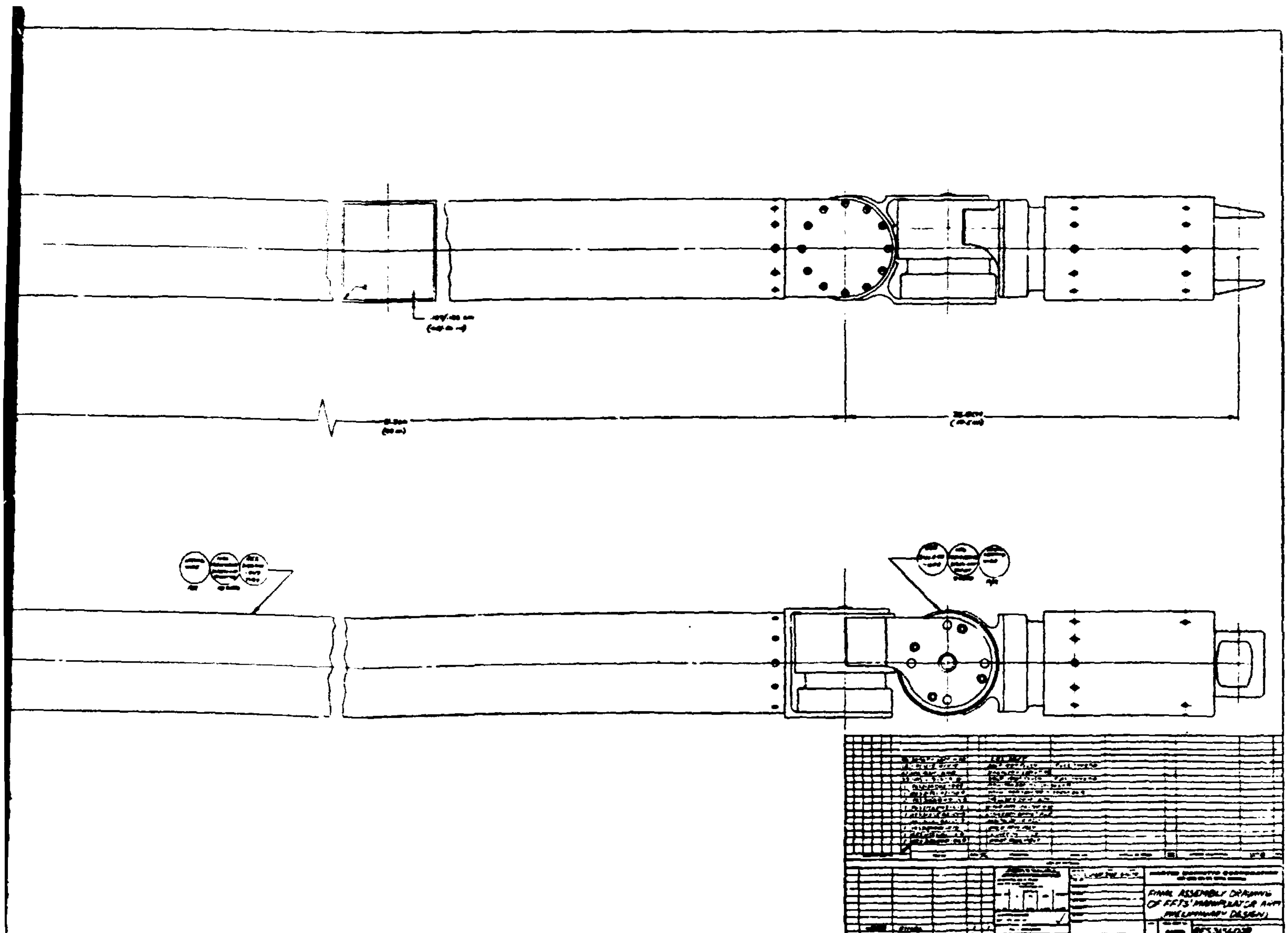


D-21 and D-22

FOLDOUT FRAME 3

accomplished by conduction and radiation. A detailed thermal interface document shall be prepared and contain, but not be limited to, the thermal mass properties, mounting conductance, view factors, orientation and emissivity and absorbitivity of the radiating surfaces. From preliminary analysis the capability of maintaining the temperature of the motor rotors in the joint actuators between -78°C to +200°C is the prime thermal design driver.

3.4.1.4 Rigging Devices - For any linkages or other devices which require accurate alignment by adjustment, the manipulator assembly shall include provisions for alignment. Location of rigging points shall be accessible for recheck of alignment without removal of any components.

3.4.1.5 Factors of Safety - Structure of the manipulator assembly and components shall be designed in accordance with the following:

(a) Structure shall not yield at 1.0 times limit load.

(b) Structure shall not fracture or become unstable at 1.4 times limit load.

3.4.1.6 Lubrication - The manipulator assembly shall be designed so that no lubrication is required during or after Acceptance Tests. Lubricants used prior to this shall meet the requirements of Paragraph 3.4.9.2.

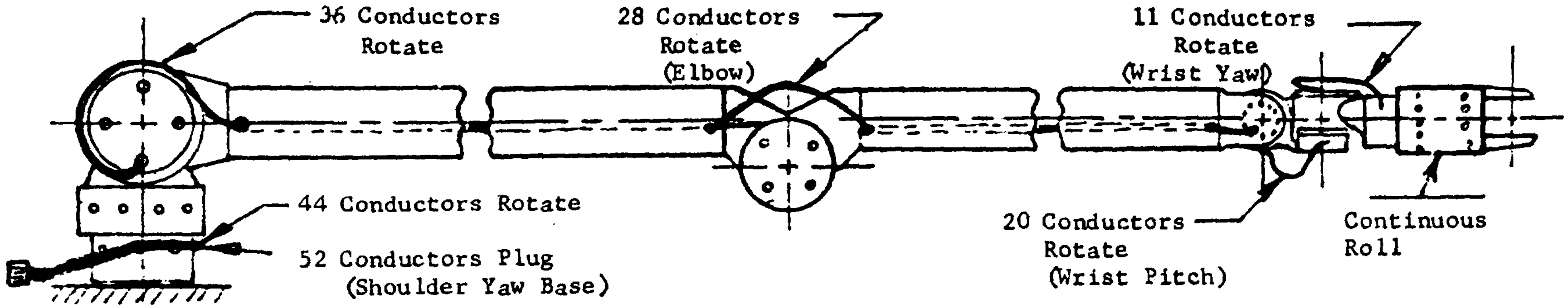
3.4.1.7 Coating and Finishes - All approved drawings defining the manipulator assembly shall identify the surface preparation, coating material, number of applications, dry coating, or plating thickness, color finish requirements process control and other requirements, to completely control finishes and processes.

3.4.1.8 Electrical Schematic - Electrical interconnections shall be in accordance with the requirements of Fig. 2 herein.

3.4.2 Interface Requirements

3.4.2.1 Mechanical - The mechanical interface shall define in detail the hardware required to attach the manipulator assembly to the Free Flyer Spacecraft. In addition to size, configuration, weight and center of gravity, this definition shall include axis orientation, moment of inertia, unbalanced angular moments, alignment, and attachment procedures.

3.4.2.2 Electrical - The electrical interface diagram for the manipulator assembly shall be prepared. The detailed definition of the electrical interface shall include as a minimum, type and size of connector, and pin assignments.



System/Joint	Function	No. Required	Gage No.	Subtotal No.
End Effector	Motor Drive	2 SH	22	2
Wrist Roll	Motor Drive Tachometer Brake Common Potentiometer Common	2 SH 2 SH 1 TW 1 TW 3 TW 1 TW	22 24 24 18 24 20	12
Wrist Yaw	Motor Drive Tachometer Brake Potentiometer	2 SH 2 SH 1 TW 3 TW	22 24 24 24	20
Wrist Pitch	Motor Drive Tachometer Brake Potentiometer	2 SH 2 SH 1 TW 3 TW	22 24 24 24	28

System/Joint	Function	No. Required	Gage No.	Subtotal No.
Elbow Pitch	Motor Drive Tachometer Brake Potentiometer	2 SH 2 SH 1 TW 3 TW	22 24 24 24	36
Shoulder Pitch	Motor Drive Tachometer Brake Potentiometer	2 SH 2 SH 1 TW 3 TW	22 24 24 24	44
Shoulder Yaw	Motor Drive Tachometer Brake Potentiometer	2 SH 2 SH 1 TW 3 TW	22 24 24 24	52

Notes: 2 SH = 2 Conductor Shielded
1 TW = 1 Conductor Twisted to Common
3 TW = 3 Conductor Twisted to Common

Figure 2 Electrical Cable Routing and Wire Specifications

3.4.3 Identification for Traceability

3.4.3.1 Identification - Identification and marking of the manipulator assembly and parts shall be in accordance with MIL-STD-130. Nameplates shall be used, where applicable, in accordance with the format of MS24123 for identification. Devices within the assembly shall be identified by a part number and serial number assigned by the supplier. Nameplates on the assembly shall include at least the following information:

- Manipulator part number
- Approved nomenclature
- Manufacturer's part number
- Manufacturer's name or trademark
- Model designation
- Serial number (as specified in the Procurement Agreement)
- Contract number - (as specified in the Procurement Agreement)

3.4.3.2 Traceability - Each manipulator assembly component shall be assigned a part number and a serial number. Records shall be maintained (at each level) which show configuration, processing, fabrication, and test history data. Each part and material used in the assembly shall have the part or material supplier's lot identification recorded.

3.4.4 Electromagnetic Compatibility - The manipulator assembly shall meet the requirements as per the Free Flying Teleoperator System Specification.

3.4.5 Malfunction Isolation - The manipulator assembly shall have test points for use in malfunction isolation and checkout of components. These test points shall be brought out of the component on a separate checkout connector. The design of the circuits which interface with the checkout connector shall be such as to insure that operation will not be impaired by normally functioning test equipment. Additionally, the test points shall be protected such that degradation will not result by short circuits from the test point to ground, power or adjacent test points.

3.4.6 Interchangeability - Like assemblies, components, devices and parts shall be fully interchangeable both physically and functionally.

3.4.7 Redundancy - The design of the manipulator assembly which incorporates redundancies shall include a means of verifying satisfactory operation of each redundant path at any time the system requires testing. Redundant items shall be located to ensure that an event which damages one will not damage the other.

3.4.8 Single Failure Points - The manipulator assembly shall be designed so that a single point failure shall not affect astronaut or ground personnel safety, cause loss of a flight vehicle or module, prevent or compromise accomplishment of a primary mission objective or cause a launch to be rescheduled.

3.4.9 Materials Parts and Processes - Materials, parts and processes shall be of the highest quality compatible with the requirements specified herein.

3.4.9.1 Dissimilar Metals - Unless suitably protected against electrolytic corrosion, dissimilar metals, as defined in MS33586, shall not be used in direct physical contact. Any protection used shall offer a low impedance path to radio frequency currents. The manipulator assembly shall be designed so that no failures will occur due to stress corrosion resulting from exposure to specified natural and induced environments or from fluids used in or on the components of the manipulator assembly during fabrication, cleaning, flushing, inspecting, testing or operating.

3.4.9.2 Non-Metallics - Non-metallics shall not be used on the manipulator assembly. If non-metallics are required they shall be justified through intended use, past use, amount used, mechanical properties, and their resistance capabilities to flammability and offgasing.

3.4.9.3 Standard Parts - NASA, Air Force-Navy (AN), Military Standards (MS) or joint Air Force-Navy (JAN) standard parts shall be used in the manipulator assembly where applicable. Maximum economic standardization of parts and components shall be provided. Where identical or similar functions are performed in more than one application within the system, effort shall be made to use only one item design for all system applications.

3.4.9.4 Processes

3.4.9.4.1 Workmanship - The manipulator assembly, including all parts and components shall be designed, constructed and finished in a quality manner. Defective plating, painting, riveting, machine-screw assembly, welding, brazing, de-burring, cleaning, and defective marking of parts and assemblies shall be cause for rejection and rework. Manufacturing practices shall be followed that will produce quality equipment.

3.4.9.4.2 Welding - Resistance Welding (spot and seam) shall be in accordance with MIL-W-6858. Fusion welding of steel and corrosion resistant steels shall be in accordance with MIL-W-6811. Fusion welding of aluminum shall be in accordance with MIL-W-8604.

3.4.9.4.3 Cleaning - The manipulator assembly and parts shall be cleaned in accordance with TBD .

4.0 QUALITY ASSURANCE PROVISIONS

4.1 General - The requirements presented in Section 3 will be verified by test or assessment as specified in this Section. Specific test and assessment types or methods for the various Section 3 requirements are identified in Table 4-1.

4.1.1 Test Types - Test types include the following: 1) Development, 2) Qualification, 3) Acceptance - Manipulator Contractor, Acceptance - System Integrator, and Acceptance - Shuttle Integrator. A brief definition of these tests as used herein is as follows.

4.1.1.1 Development Test - Development tests shall verify feasibility of the design approach and provide confidence in the ability of the hardware to pass qualification tests. Tests shall be performed primarily to acquire data to support the design and development processes; however, development test data may also be used in lieu of qualification test if the development hardware meets the requirements for qualification hardware (i.e., is identical in performance, configuration and fabrication to the space vehicle hardware). Development test performed in lieu of qualification tests will be subjected to the same controls and constraints as a qualification test. Performance requirements of Section 3 to be verified by development tests are specified in Table 4-1.

4.1.1.2 Qualification Test - Qualification tests shall verify that hardware identical in performance, configuration, and fabrication to the space vehicle hardware meets the performance and design requirements under anticipated operational environments of the applicable End Item Specification. Tests shall be conducted as a formal demonstration to show a level of confidence, performance and design adequacy.

Qualification testing shall be performed at the component or assembly level where applicable. The qualification test requirements shall be defined in the Manipulator General Test Plan, Component Qualification Test Plan (TBD).

4.1.1.3 Acceptance Test - The acceptance tests performed on the manipulator shall verify that the manipulator system (end-item) conforms to applicable performance/design requirements. Three basic acceptance tests are envisioned: Manipulator contractor, Manipulator/Vehicle integrator (could be same location as Manipulator Contractor) and Shuttle Integrator (ETR or WTR).

(a) Acceptance Tests performed on the Manipulator/Vehicle verify the interface performance/design requirements which cannot be verified at the level of the individual end-item.

(b) Acceptance Tests performed at the launch site are to verify that the flight systems will meet mission performance requirements as an integrated "system" and are physically and operationally compatible with mating hardware, systems, and ground support equipment.

4.1.2 Assessment Methods - Assessment methods include: 1) similarity, 2) analysis, 3) inspection, and 4) validation of records. A brief definition of the methods as used herein follows:

(a) Similarity - Testing shall not be required if it can be demonstrated, by review of prior test data or application of hardware, that the article is similar or identical in design and manufacturing process to another article that has previously been qualified to equivalent or more stringent environmental criteria (e.g., Skylab, Apollo and/or Gemini hardware).

(b) Analysis - Analytical techniques (e.g., systems engineering analysis, statistics, modeling, etc.) may be used in lieu of or in conjunction with testing to relate test data at earth-level conditions to orbital requirements (e.g., thermal, operational sound level, leak, etc.).

(c) Inspection (End-Item) - Inspection techniques (e.g., verification of compliance with drawings, wire coding, material compliance, etc.) may be used in lieu of or in conjunction with testing to verify design features (e.g., habitability, mounting and storage provisions, bonding, service access).

(d) Validation of Records - Validation of manufacturing records (e.g., inspection, material, assembly, etc.) or other records may be used in lieu of or in conjunction with testing/analysis to verify compliance with the requirements.

Table 4-1 Verification Requirements Matrix

Requirements for Verification

Verification Method:

1. Test
   A. Development
   B. Qualification
   C. Acceptance -
   D. Acceptance -
   E. Acceptance -

2. Assessm
   a. Simil
   b. Analys
   c. Inspection
   d. Validation of Records

(N/A - Not applicable)

Section 3 Requirement	Verification Methods N/A	A	B	C	D	E	Comments
3.0 thru 3.?	X						
3.3	X						
3.3.1	X						
3.3.2	X						
3.3.2.1	X						
3.3.2.1.1		1		2c			
(a)		1		2d			
(b)		1	1	2d			
(c)		1	1	2d			
3.3.2.1.2							
(a)		1	1	2d			
(b)		1	1	2d			
(c)		1	1	2d			
(d)		1	1	2d			
3.3.2.1.3		1					
(a)				2b			
(TBD)							

5.0 PREPARATION FOR DELIVERY

N/A

6.0 NOTES

6.1 References

1. NASA Contract NAS8-30266 "Statement of Work - Enclosure #1" Baseline Free-Flying Teleoperator System. Sept., 1973.

2. "Space Shuttle Payload Accommodations" JSC07700, Vol XIV, Rev B, December, 1973.

3. "The 1973 NASA Payload Model", National Aeronautics and Space Administration, October, 1973.

4. "Shuttle Remote Manned Systems Requirements Analysis", Contract NAS8-29904 Preliminary Final Report, MCR-73-337 (Vols. I-III), Martin Marietta Corporation, Denver, Colorado, December, 1973.

6.2 Abbreviations - TBD

E. SIMULATION

1. Introduction

The purpose of the Slave Manipulator Arm (SMA) simulation was fourfold:

1. Evaluate the comparative merits of unilateral rate and bilateral position control,
2. Determine the functional capabilities of the newly fabricated manipulator arm,
3. Examine the operational qualities of the newly constructed nongeometric bilateral controller,
4. Investigate the usefulness and workability of the data displays and operator controllable functions incorporated in the operator's control console.

Foremost of the simulation goals was an attempt to answer the much debated question, "Is a bilateral force reflecting manipulator system actually required to perform the various tasks applicable to a Shuttle or Free Flyer articulated manipulator?" To answer this question, both unilateral rate and bilateral force reflecting control law equations were developed to yield highly versatile systems capable of incorporating the desired features, as determined from previous Martin Marietta contractual efforts in the remote manipulator field.

Both unilateral and bilateral control techniques utilized a spherical base coordinate system and permitted applied manipulator forces and moments, derived from the contr[illegible]ations, to be displayed at the operator's console. To [illegible]ble force and motion reflecting ratio and the inclusion of position indexing for bilateral control, a nongeometric, sliding base, force reflecting controller was developed. Being the only known bilateral nongeometric control system in existence, not only the merit of the control philosophy but also the operational qualities of the controller were to be determined. To facilitate manipulator control using both the rate and position schemes, the operator's console included the following functional controls:

1. Variable force and motion reflecting ratios for position control,
2. Variable translation and rotation controller sensitivity for rate control,
3. Selection of wrist attitude control:
   a. manual control
   b. range hawk control
   c. full hawk control
4. Iris, focus, and zoom control of television camera lens,
5. Manipulator applied forces and moments displayed via meter readouts,
6. Actual gimbal positions displayed via meter readouts,
7. Warning indicators revealing 70% to 90% of manipulator maximum force or torque was being utilized,
8. Mono and stereoscopic television displays of remote work site.

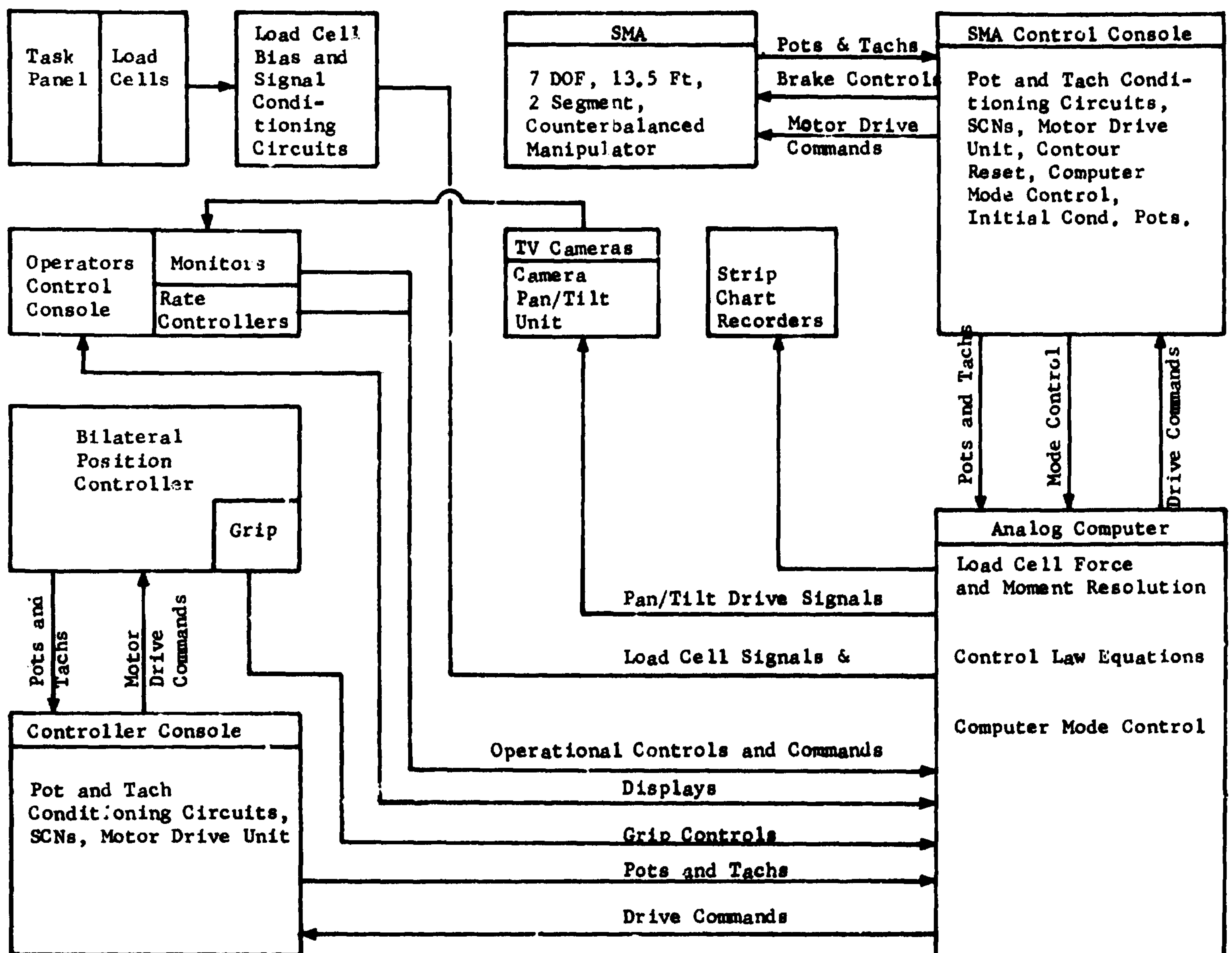
The final purpose of the simulation was to investigate the need and usefulness of each above control or presented information with respect to accomplishing a set of pre-determined tasks.

II. Simulation Equipment

An information flow block diagram identifying the signals going to and from each piece of hardware used in the simulation is shown in Figure II-1. In the following, a description and the function of each hardware item is presented.

Slave Manipulator Arm (SMA) - The major piece of equipment utilized in this simulation was the SMA, a 13.5 ft long, 7 degree of freedom (DOF), 2 segment (6 ft length each segment), totally counterbalanced, manipulator arm. This arm, shown in Figure II-2, was used to simulate an actual manipulator arm attached to the free flyer. The 7th DOF (shoulder roll) was not used in this sumulation. The arm was mounted in a configuration which resulted in a yaw, pitch, pitch, pitch, yaw, roll gimbal sequence, matching that of the FF manipulator. The manipulator wrist segment is approximately 18 inches long.

The arm joints contain dc torque drive motors, tachometers, brakes, gear trains, and potentiometers. The motors, tachometers and brakes are located on the input shaft to the gear trains, and the potentiometers are driven from the center gear of the three-pass gear trains. As described in Section III, the motors, tachometers and potentiometers are used in various ways to implement different types of control systems for actual arm operation. The SMA also has an operational terminal device (see wrist assembly close-up, Figure II-3), and provisions for mono or stereo TV cameras just behind the terminal device (not used in this simulation). Other SMA joint characteristics are summarized in Table II-1.



SMA = Slave Manipulator Arm
SCN = Servo Compensating Networks

Figure II-1 Simulation Hardware Components and Information Flow

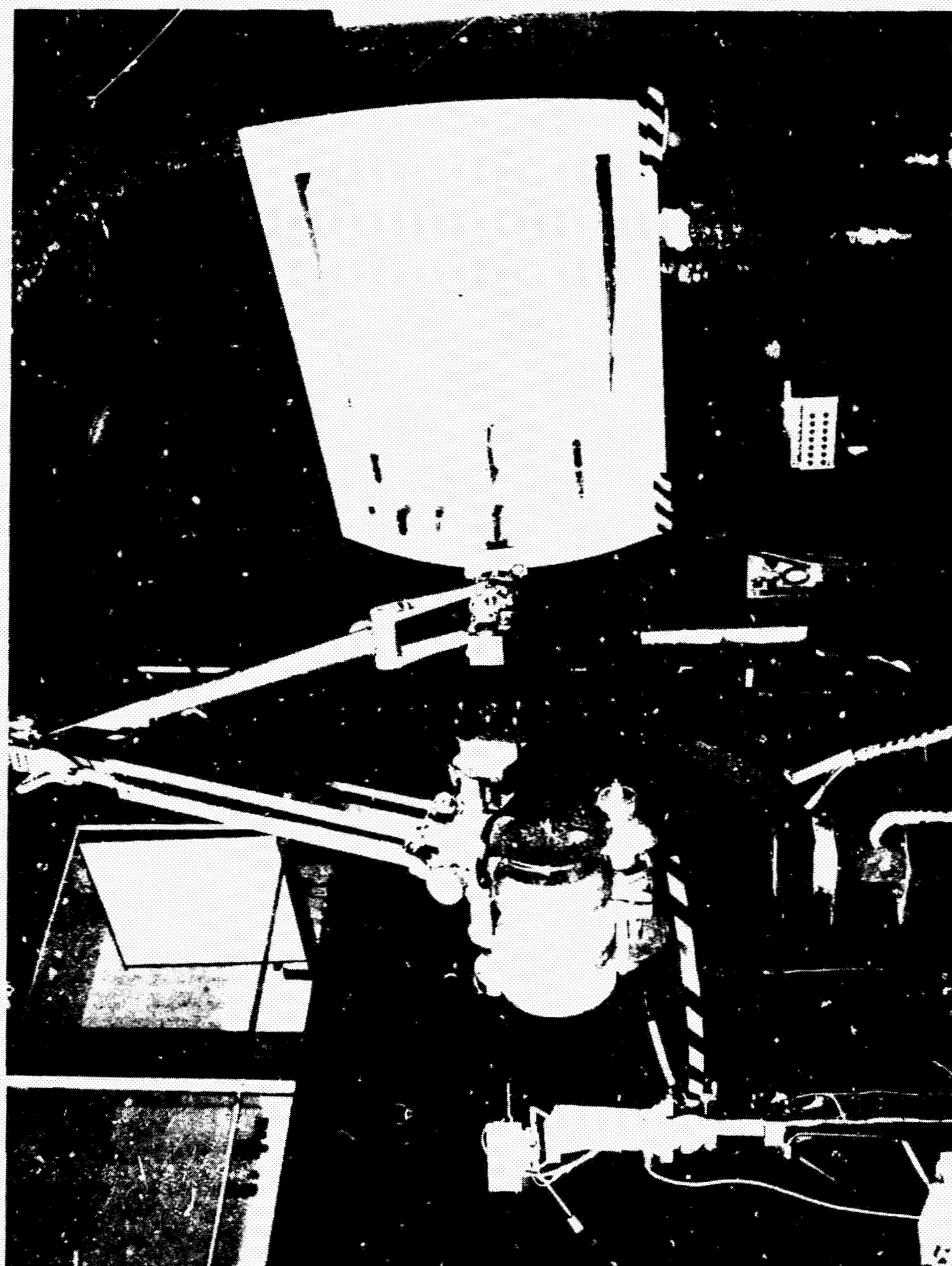


Figure II-2 Slave Manipulator Arm (SMA)

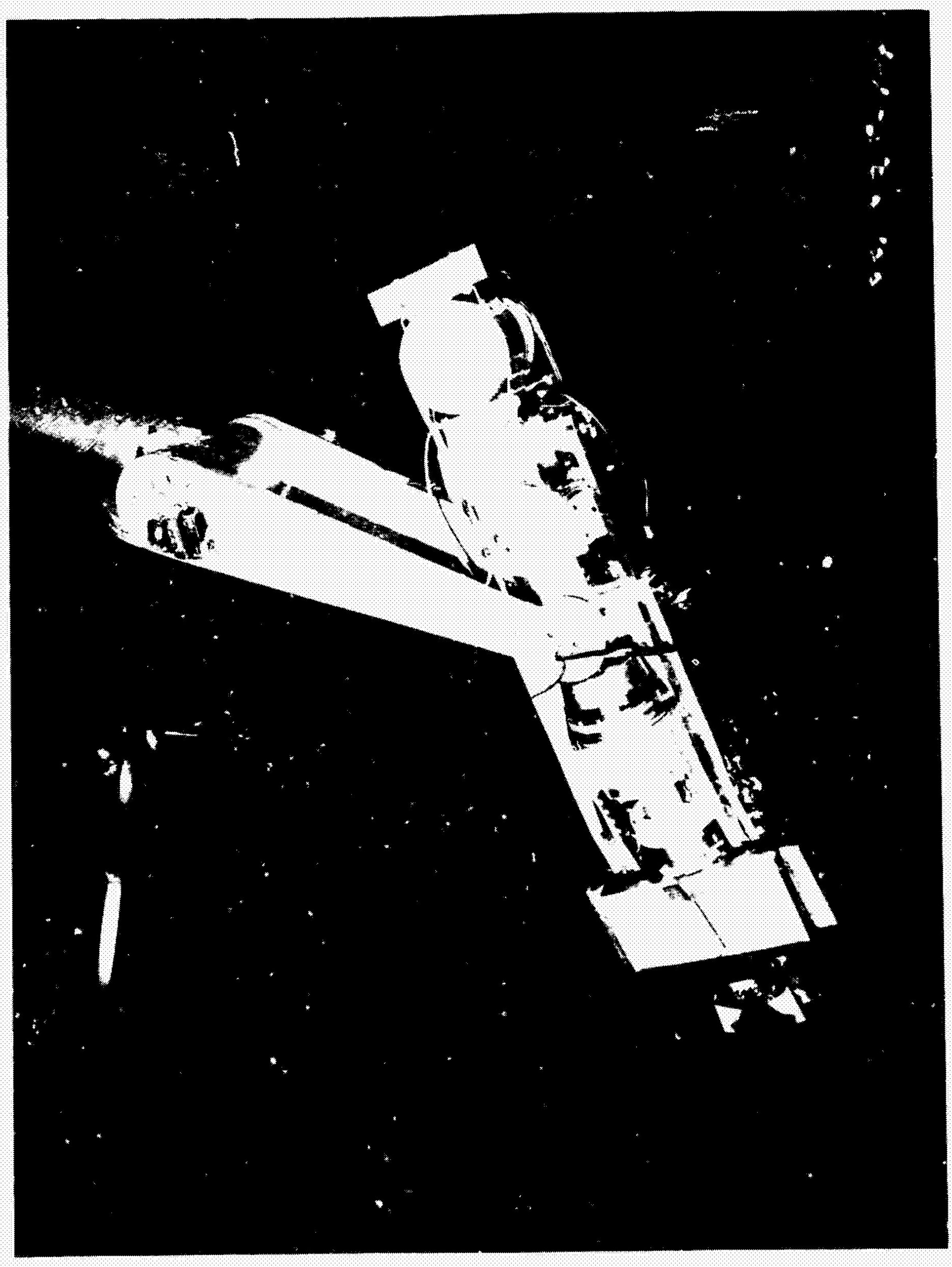


Figure II-3 SMA Wrist Assembly

TABLE II-1 SMA JOINT CHARACTERISTICS

DOF	Stall Output Torque (ft-lbs)	Gear Ratio	Angular Travel (Degrees)	Maximum Angular Rates (Deg/Sec)	Joint Backlash (Arc Min.)	Back Drive Torque (ft-lbs)	Running Friction (ft-lbs)
Shoulder Yaw Ψ_s	114	110	± 200	30	2	6	.12
Shoulder Pitch θ_s	120	110	+ 75 - 150	30	2	1.5	.03
Shoulder Roll ϕ_s	72	50	± 200	6			
Elbow Pitch θ_e	120	112.7	+ 10 - 160	30	1.7	18	.36
Wrist Pitch θ_w	48	112.7	± 130	30	.7	1.1	.02
Wrist Yaw Ψ_w	33	112.7	± 80	30	3.0	1.0	.02
Wrist Roll ϕ_w	13.5	112.7	± 200	30	0	1.5	.03

The SMA static deflection data is presented in Table II-2. The table shows the deflection due to both structural and gear train flexibility. The natural frequency of the arm (when fully extended and brakes engaged) is approximately .7 Hz with a critical damping factor of 15%.

The motion resolution of the SMA was determined by measuring the minimum possible movement of the terminal device for very small input commands. It was found that all control systems could input commands smaller than that required to move the arm. Eventually, the small commands (inputted by small pulses) increased the joint torque until stiction was overcome and the arm moved. This resulting motion for all six degrees of freedom is listed in Table II-3. The SMA static force resolution was determined in the same manner, i.e. by small pulse input commands, when the arm was rigidly attached to the load cell array. In this case, the minimum force change from an impulse was better than the resolution of the load cell array. It is estimated that SMA forces at the terminal device can be controlled to less than .2 lbs and the torques to less than .4 ft-lbs.

SMA Control Console - The SMA Control console, shown in Figure II-4 performs numerous functions relating to controlling the slave arm. A list of the major functions follow:

1. Potentiometer and Tachometer conditioning circuits - These circuits gave gain change and bias adjust capability and noise rejection to the potentiometer and tachometer signals coming from the SMA. (These signals were sent to the computer.)

TABLE II-2 SMA STATIC DEFLECTION DATA

Segments Deflected	Deflection (in/lb)	
	Structural Only	Total with Gear Trains
Shoulder to End Effector	.10	.16
Shoulder to Wrist	.06	.14
Shoulder to Elbow	.01	.02
Elbow to End Effector		.08
Elbow to Wrist	.008	.012
Wrist to End Effector		.03

TABLE II-3 SMA MOTION RESOLUTION	
Range - 3/16 inch	Wrist Pitch - .1 Degrees
Azimuth - 1/16 inch	Wrist Yaw - .2 Degrees
Elevation - 1/8 inch	Wrist Roll - .5 Degrees

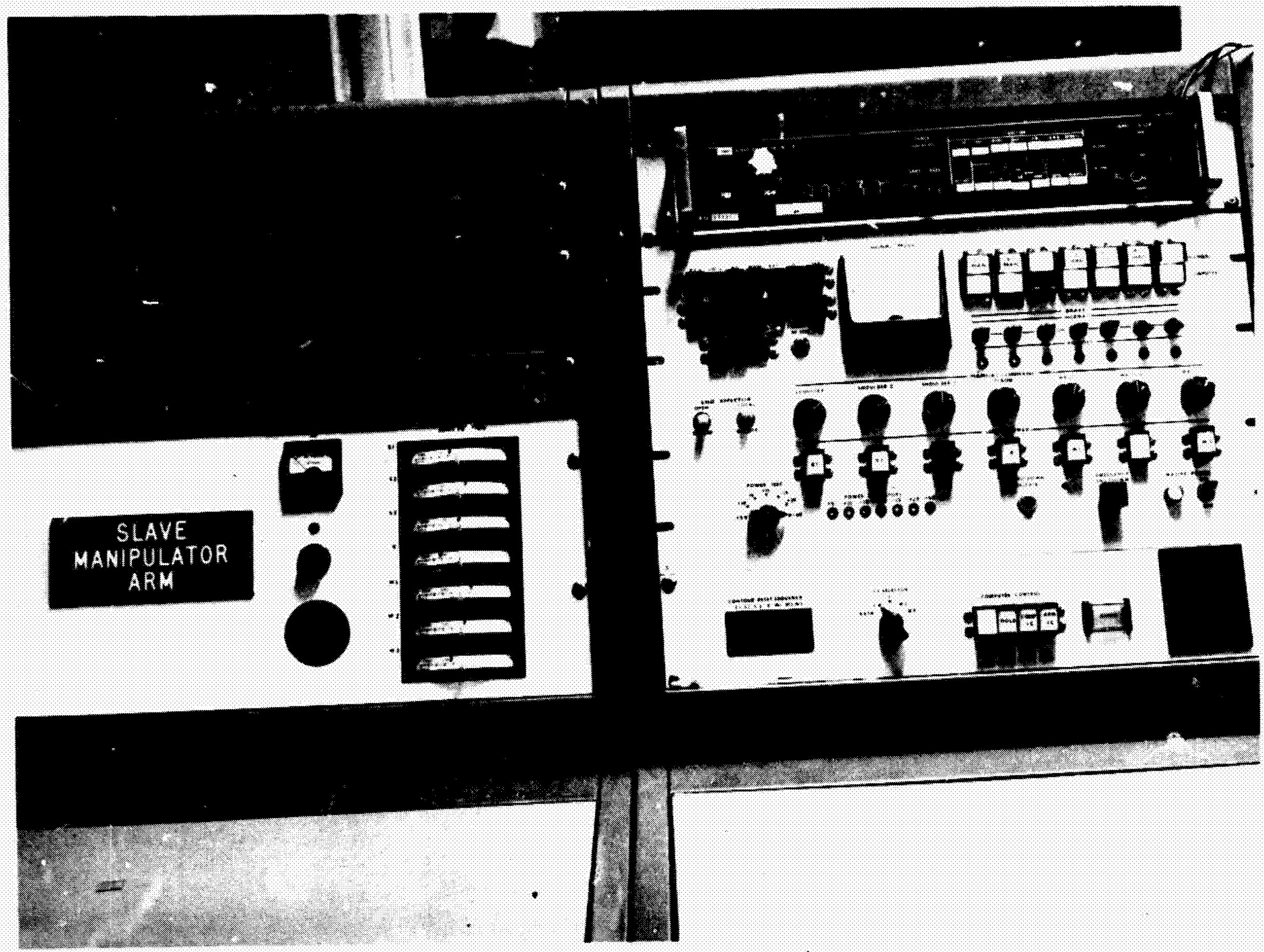


Figure II-4 SMA Control Console

2. Servo Compensating Networks (SCN) - These circuits introduced phase shift (variable by potentiometer control) into the control loops for system stability purposes.

3. Motor Drive Unit - This unit consists of power supplies, power amplifiers, and associated circuitry for supplying current to the d.c. torque motors at the SMA joints proportional to an input voltage. The amplifier outputs are current limited to protect the motors.

4. Initial Condition (IC) Pots - The console contains four sets of 7 pots (one for each DOF) for setting the arm initial position. The IC selector switch allows a choice of any one of the four sets as well as an external IC setting.

5. Contour Reset Sequence - These switches allow programming of the sequence in which the arm joints return to their IC position. This capability is useful for preventing unwanted collisions between the arm and nearby hardware. Integral with this circuitry are mode-change integrator networks which prevent step commands to the arm whenever a mode is changed.

6. Computer Control - These switches control the computer mode, e.g. operate, hold, or IC. Whenever the Hold,Comp. IC, or Arm IC switches are activated, control of the arm is always maintained in the SMA Control Console. The computer is in control only when the operate button is activated.

7. Joint Limit Circuits - These networks perform a safety function by removing power to the motors, and applying the brakes, whenever the joint angles reach preset angular limits. These limits are

variable and can be set to any plus and minus angles.

8. Local Position Loop Circuits - These circuits allow local position control of each joint from a potentiometer input. The servo power push buttons activate the torque motor power amplifiers which then close the position loop around each joint.

9. Other Control Switches - Master Power (On/Off), Emergency Shutdown, Shutdown Release, Power Test, Brakes (On, Release, Normal or Computer Control), manual/computer control, end effector open/close, end effector local/remote, and various other switches which select information for display on the digital volt meter.

10. Monitor Functions - Two TV monitors, joint angles, end effector position, and various indicator lights.

Computer - An EAI 231-R analog computer was used as the major controlling subsystem during actual arm operation. The computer was programmed with all the control law equations (see Section III) and used to close control loops around the SMA joints and the vertical sliding bilateral controller joints. Most of the control functions located on the operator's control console were interfaced with the computer which introduced the appropriate control conditions.

The computer was also programmed with the load cell equations which resolve individual load cell outputs to orthogonal forces and moments about the task panel coordinate system. These forces and moments along with control system forces and torques were recorded on strip chart recorders which are part of the computer hardware.

Approximately 1-1/2 analog consoles were used in this simulation for all the control law equations, load cell equations, and other required calculations. Each EAI 231-R analog console contains 30 Integrators, 45 Summer Amplifiers, 36 Multipliers, and 3 Resolvers.

Operator's Control Console - The operator's control console used in this simulation is shown in Figures II-5 and II-6. The console layout and design was based on simulation experiment considerations and would not necessarily resemble the space manipulator arm console. Figure II-5 shows mainly the display parameters used by the operator for determining his input commands. The displays are as follows:

1. Hazard Avoidance Indicator Lights - not used.
2. Joint Angle Indicator Light - Light flashed (and also a buzzer sounded) when any joint came within 90% of its electrical limit in either the plus or minus direction.
3. Zoom Lens Meter - Displayed the zoom lens setting in mm of the 20 to 100 mm zoom lens attached to the mono TV camera.
4. Manipulator Joint Angles - These meters displayed in degrees the actual arm joint and/or for all 7 DOF.
5. TV Monitors - The upper monitor displayed the stereo image and the lower the mono image of the TV cameras mounted on the pan/tilt unit.
6. Position Override Lights - The upper light (yellow) came on when the drive command to any joint became 70% of its maximum capability. The lower light (red) came on when the command became 90% of its maximum capability.
7. Contact Light - Not used. Contact of the arm with the task panel was known from the force and moment meters.

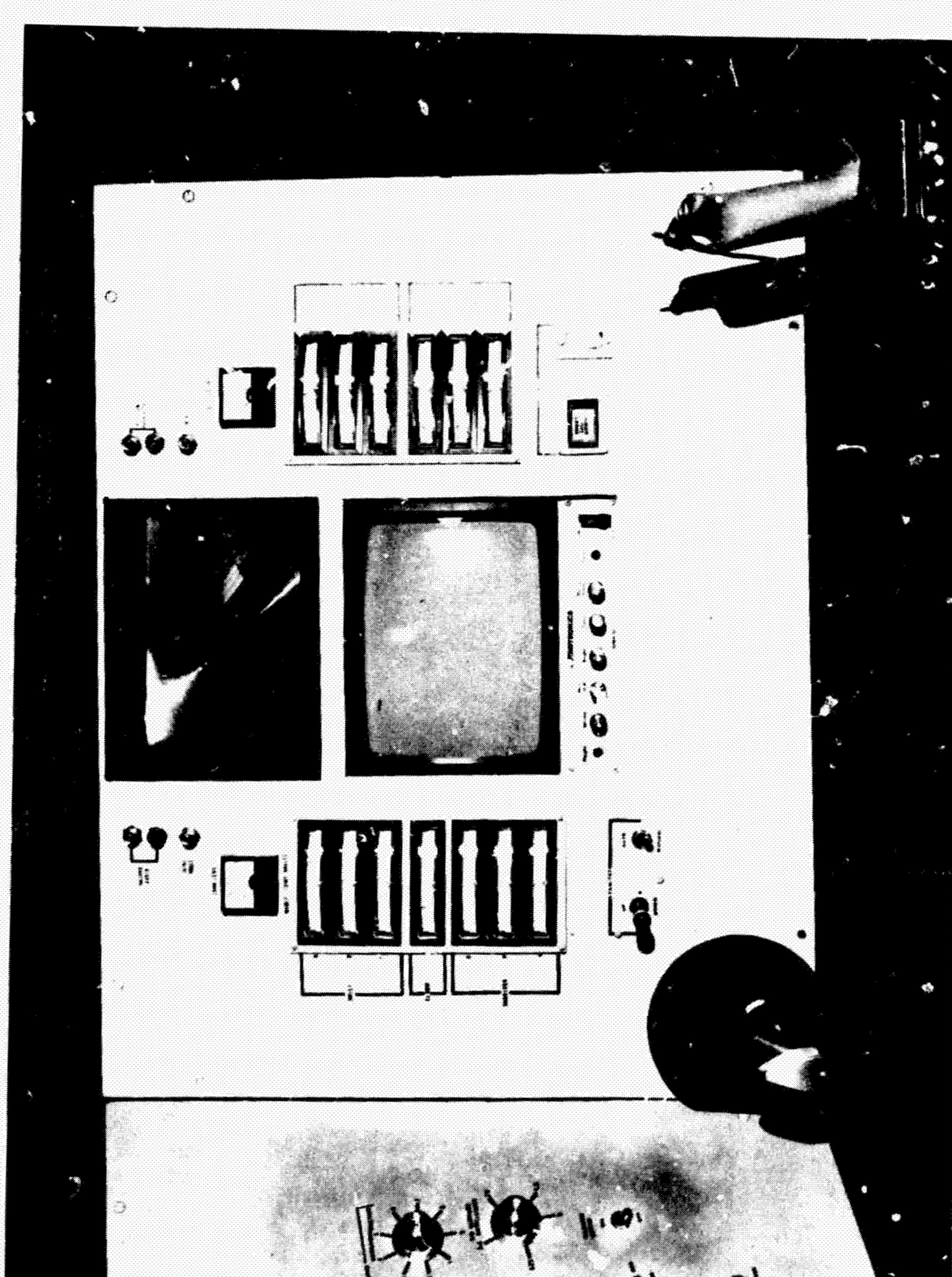


Figure II-5 Operator's Console - Center Section

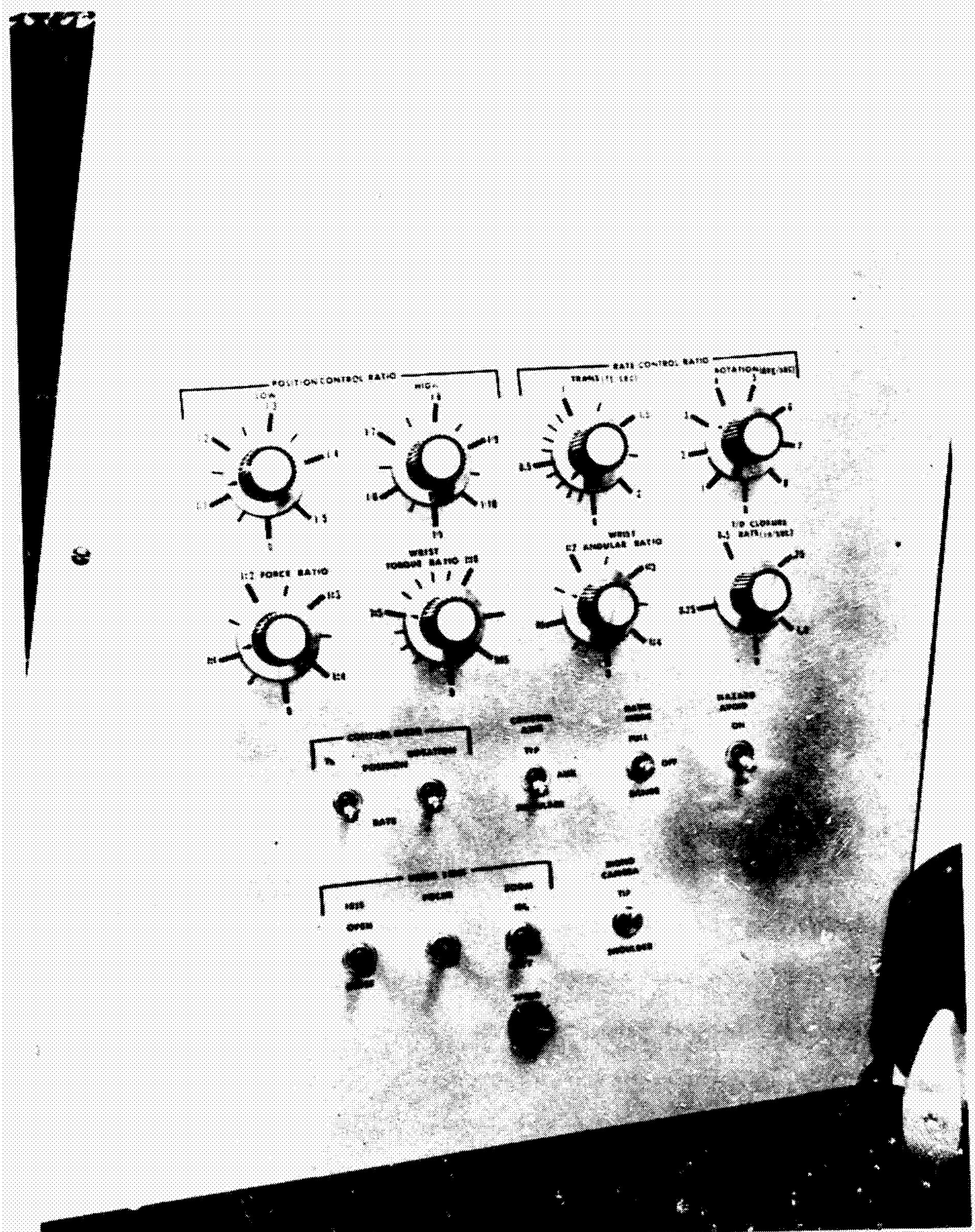


Figure II-6 Operator's Console - Left Section

8. Force and Moment Meters - These meters displayed to the operator the actual forces and moments that were being applied to the task panel. Computer function switches allowed the displays to be easily changed from load cell measured forces and moments to control law applied forces and torques. The load cell parameters were relative to the fixed task panel coordinate system while the control law parameters were relative to the range, azimuth, and elevation coordinate system for translation and the pitch, yaw, roll manipulator wrist axis for rotation.
9. Power Switches - One switch turned console power on, and the other switch performed the same function as the emergency shutdown switch on the SMA console.

The other switches or controllers shown in Figure II-5 performed control functions. These are:

1. Translational and rotational rate hand-controllers - Described in the controller section.
2. Pan/Tilt Controller - A 2-axis on/off pencil type controller used to control the pan/tilt unit on which the TV cameras were mounted.
3. Auto/Manual Switch - This switch allowed the operator to select automatic tracking (auto position) of the end effector by the TV cameras. In this position, a manual override capability was available. In the Manual position, only manual control was allowed.

Figure II-6 shows more of the control functions available to the operator. (This panel was located to the left of the operator.) These control functions are as follows:

1. Position Control Ratio (Position mode only) - These dials allowed selection of a high and a low translational motion ratio between position controller motion and slave motion. The low ratio ranged from 1:0 to 1:5 and the high from 1:5 to 1:10. The low or high ratios were selectable from a 2 position switch located on the position controller grip.
2. Rate Control Ratio (Rate mode only) - These dials allowed selection of the maximum tip velocity for translational motion and maximum angular velocity for wrist motion and rotational motion which would be obtained when the proportional controllers are deflected full. The translational velocity ranged from zero to 2 ft/sec, and the rotation rates from 0 to 8 deg/sec.
3. Force Ratio - This dial allowed selection of the force ratio between controller force felt by the operator and the slave force applied by or to the arm. The ratio was variable from 1:0 to 1:4. The implementation of this control variable was in the slave loop (see Section III on Control Laws) and effectively varied the slave position loop gain. As such, the dial also allowed varying the slave loop gain when operating in the rate mode. The result of varying the slave loop gain was the ability to vary the backdriveability and compliance of the slave.
4. Wrist Torque Ratio - This dial performed the same function as the force ratio dial except that it applied to the controller wrist joints and the slave wrist joints. The torque ratio was variable from 1:0 to 1:15. The variable backdriveability and compliance of the slave in the rate mode operation also applies.

5. Wrist Angular Ratio (Position Mode only) - This dial allowed selection of an angular motion ratio between slave wrist angles and controller wrist angles. The ratio was variable from 1:0 to 1:4.

6. T/D Closure Rate - This function was not implemented in this simulation. Its purpose would have been to vary the closure rate of the terminal device from 0 to 1 in/sec.

7. Control Mode Switches - These switches were not operational. Position or rate modes were selected from function switches on the analog computer.

8. Control Axis Switch - This switch was not operational since only one camera location was used. Its function would have been to switch monitors, and control axes, from one TV camera to another.

9. Hawk Mode - This switch allowed selection of either full, range, or no automatic terminal device attitude hold. The full and range hawk modes are explained in Section III.

10. Hazard Avoidance - Not implemented.

11. Video Lens - These three switches allowed remote control of the Iris, Focus and Zoom setting of the mono TV camera lens. The potentiometer allowed control of the speed of the the drive motors.

12. Mono Camera - The switch was not operational since no camera at the tip was used.

<u>Controllers</u> - Two types of input hand controllers were utilized in these simulations: a) Two 3-DOF Apollo type rate hand controllers used for the rate system, and b) a 6-DOF vertical sliding type bilateral

(force-feedback) hand controller used for the position mode. The two rate controllers are shown in Figure II-5, both are proportional type which means that a voltage output is obtained as a function of controller deflection. The left-hand controller operated the 3 translational DOF, range, azimuth and elevation, and the right-hand controller operated the 3 rotational DOF, pitch, yaw, roll. A switch on the rotational controller was used for remote open/close operation of the terminal device. The 6-DOF position controller and its control console is shown in Figure II-7.

The controller had the following gimbal sequence: roll, pitch, vertical slide, (for translational motion), yaw, pitch, roll (for rotational motion). Each DOF contains a dc motor, tachometer, gear train, and potentiometer such that a servo loop can be closed around each DOF. The controller characteristics are summarized in Table II-4. The manner in which the position controller was used to obtain control law inputs is covered in Section III.

The position controller grip contains three switches which could be activated by the operator while maneuvering the slave arm. One is the high/low position motion ratio previously mentioned; the second is an open/close terminal device control switch; and the third is the indexing switch. This switch when activated allows the operator to move the controller to any new position without affecting slave motion (effectively disconnects the controller from the slave).

The position controller control console performed the same functions for the controller as the SMA control console did for the slave arm.

Figure II-7 Nongeometric Bilateral Controller

TABLE II-4 VERTICAL SLIDING CONTROLLER CHARACTERISTICS

	Output Torque (ft-lb)	Gear Ratio	Angular Travel (Degrees)	Maximum Angular Rates (Deg/Sec)	Joint Backlash Arc. Min.	Back Drive Torque (ft-lbs)
Base Roll ϕ_B	22.5	107.5	$\pm$ 90	30	8	1.85
Base Pitch θ_B	22.5	107.5	+ 35 - 90	30	10	1.04
Vertical Slide ℓ_B	10 lbs (Vertical Force)	NA	$\pm$7(in.)	2(ft/sec)	.1 (in.)	.03(lb)up .01(lb)down
Wrist Yaw ψ_h	1.3	15.2	$\pm$ 180	30	16	.10
Wrist Pitch θ_h	1.3	15.2	$\pm$ 40	30	9	.10
Wrist Roll ϕ_h	1.3	16.5	$\pm$ 180	30	11	.09

The controller console contained potentiometer and tachometer conditioning circuits, servo compensating networks, motor drive units, local position loop circuits, and signal monitoring functions.

Viewing System - All slave operation was conducted by remote viewing using two television cameras mounted on a pan/tilt unit and tripod. The cameras were located at SMA shoulder pitch height (84 inches above floor level) and 65 inches to the left (-y) of the arm base. Both cameras were equipped with 20 to 100 mm zoom lenses with remote iris, focus, and zoom control. The output of one of the cameras was sent to the lower mono monitor at the operator's control console. This camera had remote iris, focus and zoom control from the console. Output of both the cameras were used to generate a Fresnel type stereo display which was presented to the operator on the upper screen at the control console. Since the mono camera was also one of the stereo pair, stereo could be seen only when the zoom setting of the mono camera matched the second camera zoom setting. This occurred at a 64 mm setting, which the operator could easily obtain using the zoom lens setting meter on control console.

No attempt was made in this simulation to simulate spatial lighting conditions. Task panel illumination was from normal room lighting, and presented no TV viewing problems.

Task Panel - The task panel used to simulate service and maintenance type tasks by spatial manipulators is shown in Figure II-8. The panel contains fixed bars, recepticles for inserting various size rods and boxes, and friction force and torque devices. Specific tasks that the operator was required to accomplish using this task panel are described in Section IV. The task panel face was located 87 inches in front (+x) of the arm base.

The task panel was mounted on a load cell array which allowed measuring and recording of all forces and moments applied to the task panel by the slave arm. This allows comparison of force and moment magnitudes applied to the panel for each task for the various control system types under consideration.

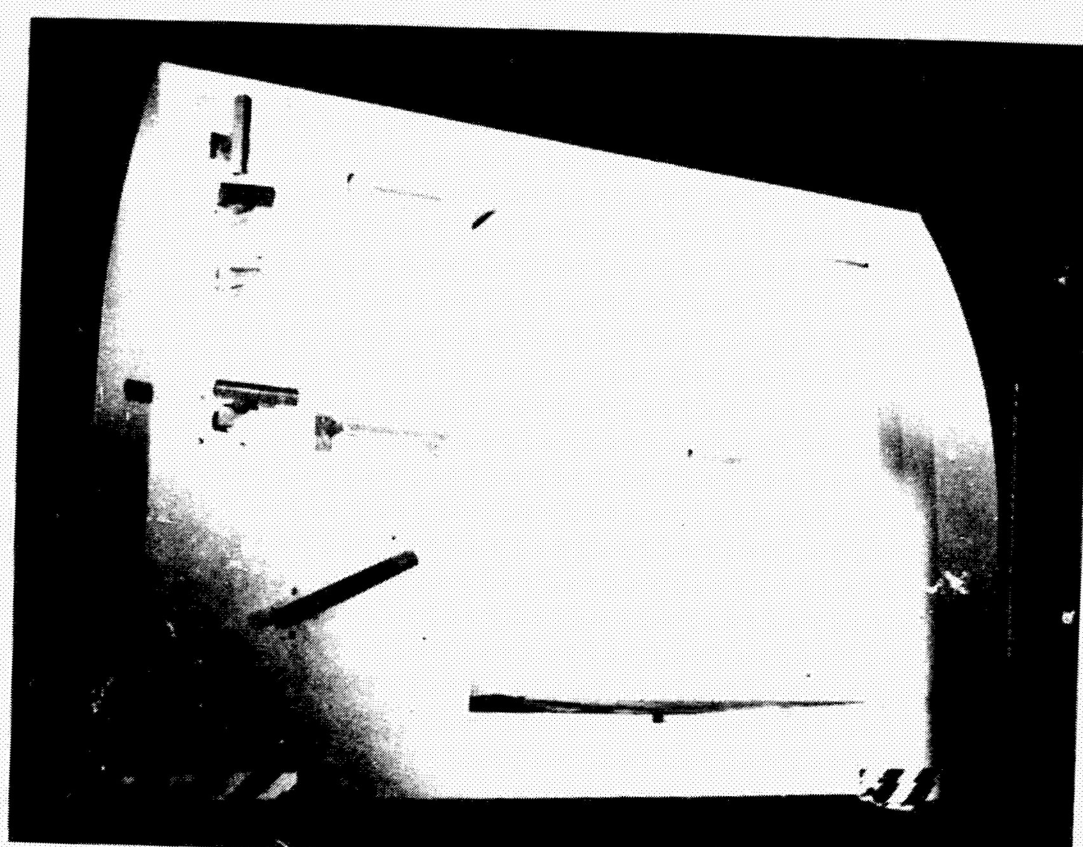


Figure II-8 Task Panel

III. Control Law Implementation

A. INTRODUCTION

Control laws refer to the equations used to interface the control input devices with the manipulator arm gimbal actuators. These laws can range from very simple to quite complex, depending upon the desired versatility to be designed into the manipulator system. One purpose of this simulation was to evaluate a set of Martin Marietta conceived control equations that are not only comparatively simple but also extremely versatile in that they accommodate both unilateral rate controllers and a bilateral force feedback position controller. The control technique is somewhat unique, as will be described momentarily, in that the operator has control of certain selectable variables, an example being the variable motion and force reflecting ratios between the bilateral position controller and the manipulator.

Preceding the present simulation, it was believed that certain space related manipulator tasks, such as module retraction-replacement, connector engagement-disengagement, probe insertion, etc., might possibly only be accomplished with a bilateral force reflecting system. Based upon this belief, an additional objective of the simulation was to compare unilateral rate control and bilateral position control when attempting to perform force related tasks. From the onset of the control law development, it was realized that to provide a fair comparison of the two systems, the unilateral rate controllers must have the dual capability of: 1. commanding manipulator rates when the arm was free to move and, 2. commanding manipulator forces when the objective was to apply a force or torque to a grasped object. For the rate controllers to succeed in performing force related tasks, it was felt that the actual forces and torques generated by the manipulator on its environment must be visually displayed to the operator. To accomplish this, the information must be obtained by actual measurements or computed from related known parameters. Since actual measurements are definitely impractical, the control equations were designed to provide the needed information which was displayed to the operator via three force and three torque meters.

B. CONTROL EQUATIONS

As revealed in the Martin Marietta contractual report "Attached Manipulator System Design and Concept Verification for Zero-g Simulation" (NAS9-13027), control of a multi degree-of-freedom articulated manipulator with a bilateral force reflecting non-geometric position controller requires that two points of comparison be selected, one on the controller and the other on the manipulator, for there no longer exists a one-to-one relationship between controller and manipulator gimbals as in a master-slave system. These two points are naturally defined as the hand grip on the input controller and the wrist gimbal assembly attachment point on the slave manipulator. The coordinate system used to define these points may be either cartesian, cylindrical, or spherical. Spherical coordinates were selected for the SMA since they are truly a "natural" coordinate system for a six or seven DOF articulated manipulator. Fig. III-1 depicts the SMA degrees of freedom and defines the range vector, azimuth, and elevation spherical parameters. Equations III-1 relates these parameters to the manipulator joint angles revealing the simplicity of using the spherical approach.

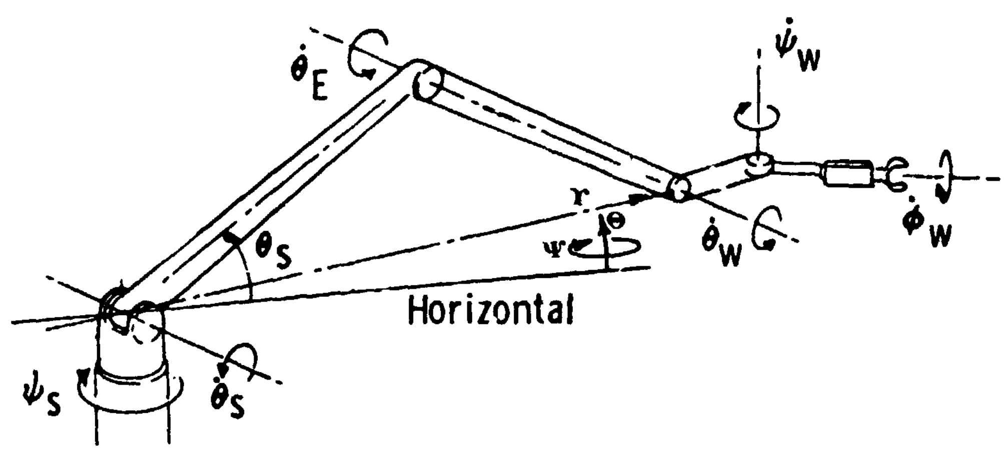


Figure III-1 SMA Degrees of Freedom

a. $r = 2Lc\gamma$, where $\gamma = \theta_e/2$ (III-1)

b. $\theta = \theta_s + \gamma$

c. $\phi = \phi_s$

As implied by Figure III-1, manipulator control in six degrees of freedom is divided into two - three degree of freedom problems. Translational control of the wrist point is provided by range, azimuth, and elevation commands originating from the bilateral position controller or the translational unilateral rate controller. Rotational control of the wrist assembly is accomplished in the position and rate modes by:

(1) Connecting on a one-to-one basis the bilateral position controller wrist gimbals with the manipulator wrist gimbals.

(2) Associating each unilateral rotational rate controller degree of freedom on a one-to-one basis with its counterpart gimbal on the manipulator wrist.

The derivation of the control laws evolved by relating manipulator wrist point control to the age old servo problem of controlling a shaft position or rate in a single degree of freedom actuator mechanism. That is, an error signal is formed between the commanded range, azimuth, elevation (RAE) or wrist pitch, yaw, roll (PYR) position or rate and the actual manipulator wrist point RAE or wrist assembly PYR values. These error signals are related through forward loop gains to forces (for translational degrees of freedom) and torques (for rotational degrees of freedom) that the manipulator must apply to its environment. (This technique is analagous to a normal servo system in which the error signal is related to an actuator torque that must be applied to the rotating shaft assembly.) Once the derived torques are obtained they can be applied directly to the wrist PYR actuators, whereas the derived translational forces must be transformed by torque distribution equations into torque values that are used to activate the shoulder and elbow gimbals.

As can be seen, the control philosophy is relatively uncomplicated which results in equations (detailed below) that when operating in spherical coordinates are quite simple. Reiterating, the dominant features of the control equations are:

(1) For bilateral control, the controller to manipulator force reflecting ratio is operator selectable and invariant with arm geometry.

(2) For bilateral control, the controller to manipulator motion ratio is operator selectable and invariant with arm geometry.

(3) For rate control, the input control devices serve dually to command rates for the free moving arm and to command forces and torques for the static situation.

(4) No position or rate loops exist around any gimbal since all joint actuators are driven with torque commands derived by the control law equations.

(5) The servo system stability analysis becomes involved due to the nonlinear nature of the control laws - although the final design servo electronics are by no means complicated.

Three Control Modes

As stated previously, the simulation evaluated both unilateral rate and bilateral position control techniques. Actually, two types of unilateral rate equations were used, yielding a total of three control modes simulated.

The first rate approach, denoted "rate-rate", utilized the comparison of a commanded range, azimuth, elevation or attitude rate with the actual range, azimuth, elevation or attitude rates of the manipulator. A rate error signal was formed and related to manipulator applied forces and torques. Thus, when in contact with an object, no forces or moments were produced unless the rate controllers were deflected and held, the magnitude of the applied forces and moments being proportional to controller displacement. The second rate technique, termed "rate-position", integrated the rate input commands which were then compared with actual range, azimuth, elevation and attitude positions of the manipulator. The position error signals formed were proportional to the desired forces and torques. In contrast to the "rate-rate" approach, a specific controller displacement now commanded a time rate increase of the force or torque applied to a grasped object. Thus, a constant applied pressure could be maintained by first deflecting the input controller(s) followed by a return to the neutral position. Note, if an objective was to relieve all forces and moments applied by the manipulator, the "rate-position" technique did not allow the operator to simply use the "hands-off" approach, for residual forces invariably existed when no input commands were present.

The control equations associated with each gimbal of the manipulator and all controller degrees of freedom for both rate approaches and the bilateral scheme are presented in the following section.

Rate-Rate Control

1. Range

Fig. III-2 depicts the control equations and signal flow associated with the range degree of freedom.

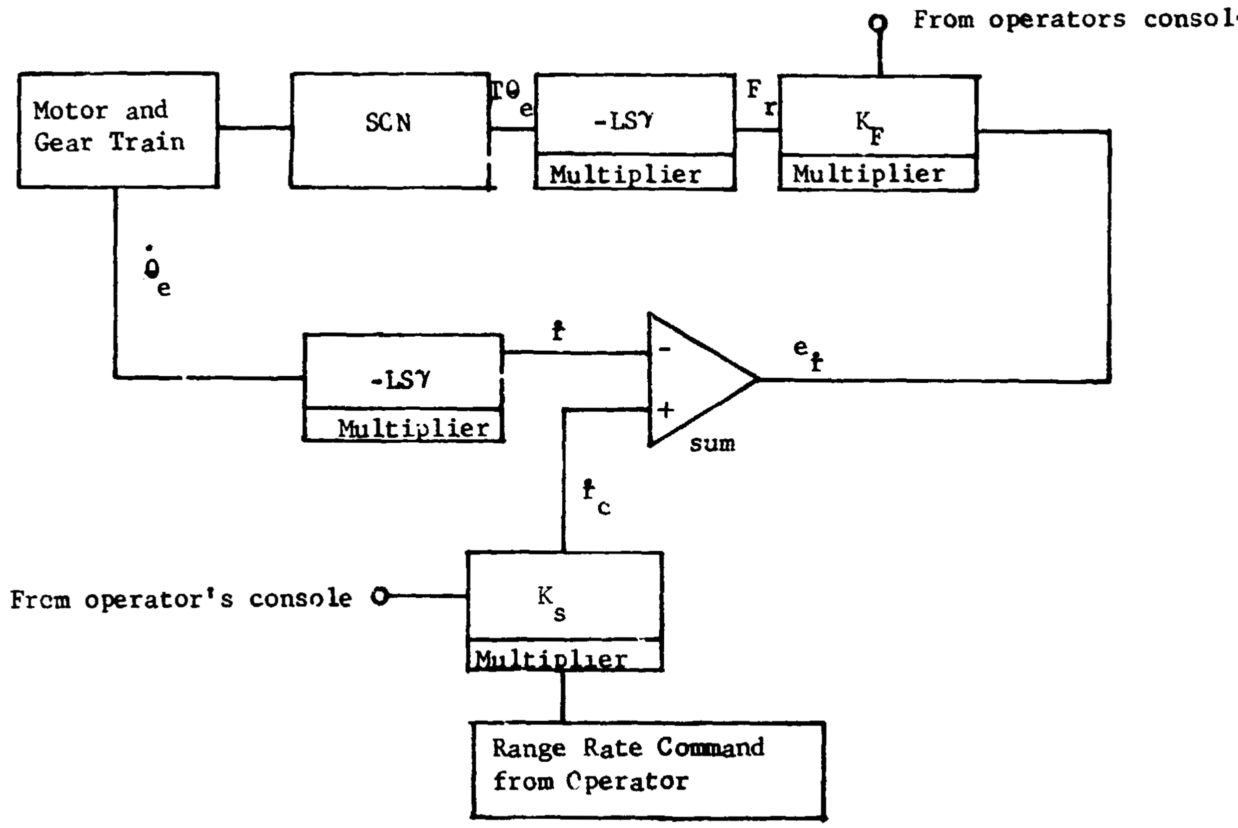


Figure III-2 "Rate-Rate" Range Control Loop

The notation of Figure III-2 is defined as follows:

a. $\dot{\theta}_e$ = manipulator elbow joint rate

b. L = upper and lower manipulator segment length

c. γ = $1/2\ \theta_e$

d. $S\gamma$ = Sine (γ)

e. $\dot{r}$ = actual range rate

f. $\dot{r}_c$ = commanded range rate

g. $e_{\dot{r}}$ = range rate error signal

h. K_ε = controller sensitivity gain

i. K_F = range forward loop gain

j. F_r = signal representing force to be applied in range

k. $T_{\theta e}$ = elbow actuator torque command

l. SCN = servo compensation network

The range rate input command is operated on by the controller sensitivity gain K_s which is an operator selectable variable. The resultant signal is compared with the actual range rate of the manipulator to form a range rate error signal $(e_{\dot{r}})$. This error is related, by the operator controllable forward loop gain K_F, to the desired range force the manipulator must apply.

The force value is then conditioned by the torque distribution equation -LSY to reveal the desired actuator torque. The servo conditioning network controls the phase of the signal to assure satisfactory loop stability.

2. Azimuth

Fig. III-3 reveals the azimuth degree of freedom control loop.

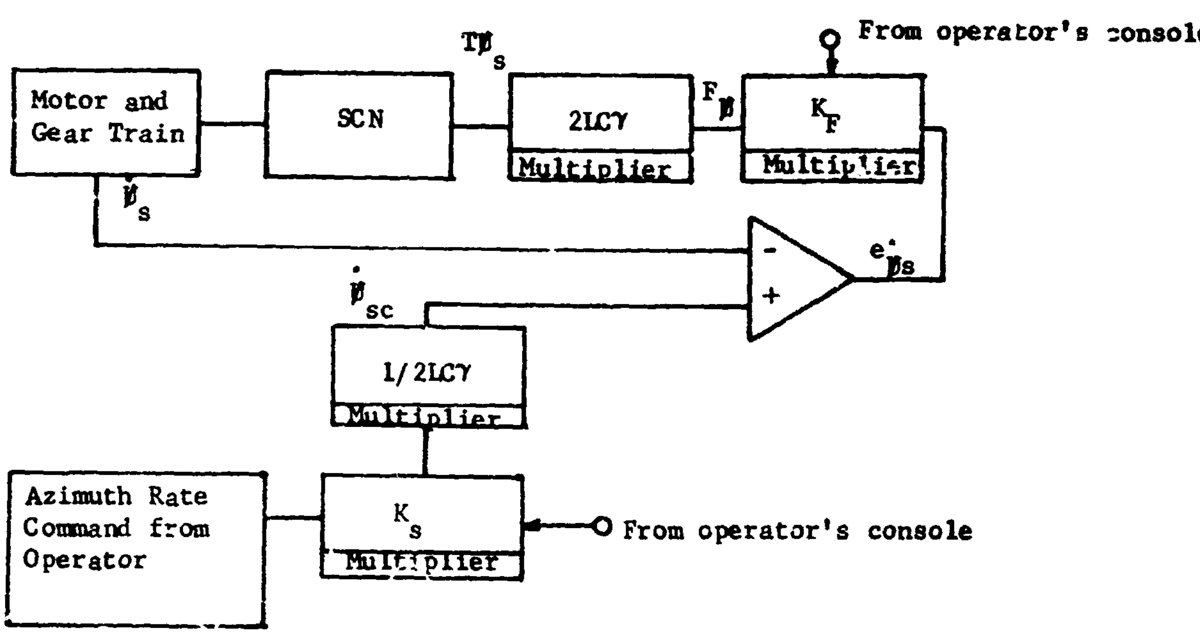


Figure III-3 "Rate-Rate" Azimuth Control Loop

a. $\dot{\psi}_s$ = manipulator shoulder yaw rate

b. L = manipulator segment lengths

c. γ = $1/2\ \theta_e$

d. $C\gamma$ = Cosine (γ)

e. $\dot{\psi}_{sc}$ = commanded shoulder yaw rate

f. $e_{\dot{\psi}}$ = azimuth rate error signal

g. K_s = controller sensitivity gain

h. K_F = azimuth forward loop gain

i. F_{ψ} = signal representing force to be applied in azimuth direction

j. $T_{\psi s}$ = shoulder yaw torque command

k. SCN = servo compensation network

The azimuth rate input command is conditioned with the gain K_s then divided by the range vector length ($2LC\gamma$) to produce a commanded manipulator shoulder yaw gimbal rate. This command is compared with the actual joint rate to yield an azimuth rate error signal. The error value is then processed using the same philosophy as described in the above range loop.

3. Elevation

Fig. III-4 shows the elevation control equations.

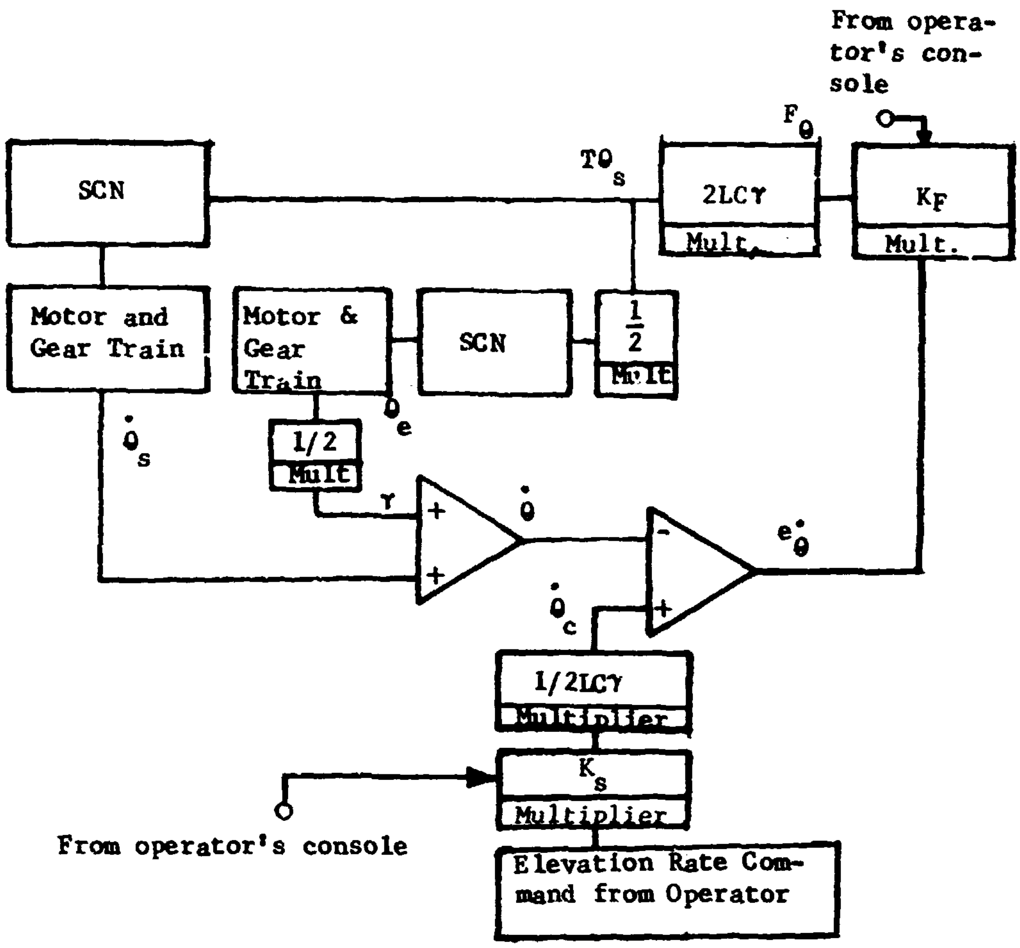


Figure III-4 "Rate-Rate" Elevation Control Loop

a. $\dot{\theta}_s$ = shoulder pitch gimbal rate

b. $\dot{\theta}_e$ = elbow gimbal rate

c. $\dot{\theta}$ = elevation rate

d. $e_{\dot{\theta}}$ = elevation rate error signal

e. γ = $1/2\ \theta_e$

f. L = manipulator segment lengths

g. $C\gamma$ = Cosine (γ)

h. K_s = controller sensitivity gain

i. K_F = elevation forward loop gain

k. F_{θ} = signal representing force to be applied in elevation direction

l. $T_{\theta s}$ = shoulder pitch torque command

m. SCN = servo compensation network

n. $\dot{\theta}_c$ = commanded elevation rate

The elevation control loop operates on the same principle as do the range and azimuth loops. Note that the derived elevation force results in torque commands that must be sent to both the shoulder and elbow pitch gimbals.

4. Wrist Pitch

The wrist pitch, yaw and roll gimbals are identical in their control technique and therefore only the pitch joint is detailed, as shown in Fig. III-5.

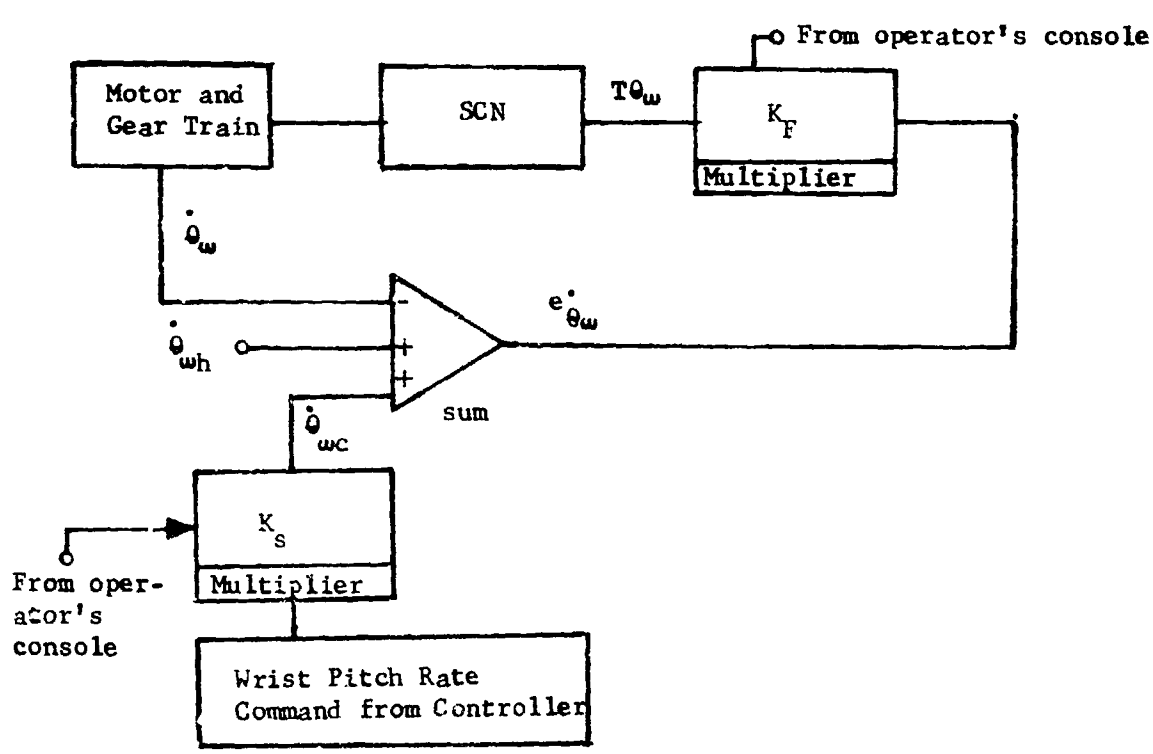


Figure III-5 "Rate-Rate" Wrist Pitch Control Loop

a. $\dot{\theta}_\omega$ = wrist pitch gimbal rate

b. $\dot{\theta}_{\omega c}$ = commanded wrist pitch rate

c. $\dot{\theta}_{\omega h}$ = wrist pitch rate hawk command

d. K_s = controller sensitivity gain

e. K_F = forward loop gain

f. $e_{\dot{\theta}\omega}$ = rate error signal

g. $T_{\theta\omega}$ = wrist pitch torque command

h. SCN = servo compensation network

The control sensitivity (K_s) and torque (K_F) gains are operator selectable as in the RAE loops. The presence of the input rate hawk command ($\dot{\theta}_{\omega h}$) is determined by the operator as will be fully detailed later in this section.

Rate-Position Control

As discussed previously, "rate-position" control differs from "rate-rate" in that the input rate commands are integrated and compared with arm position values. Integrators are incorporated into the system and gimbal data is now secured in the form of joint angular positions.

Due to the minor differences between the two types of control, only the range degree of freedom, Fig. III-6, is presented to emphasize the changes.

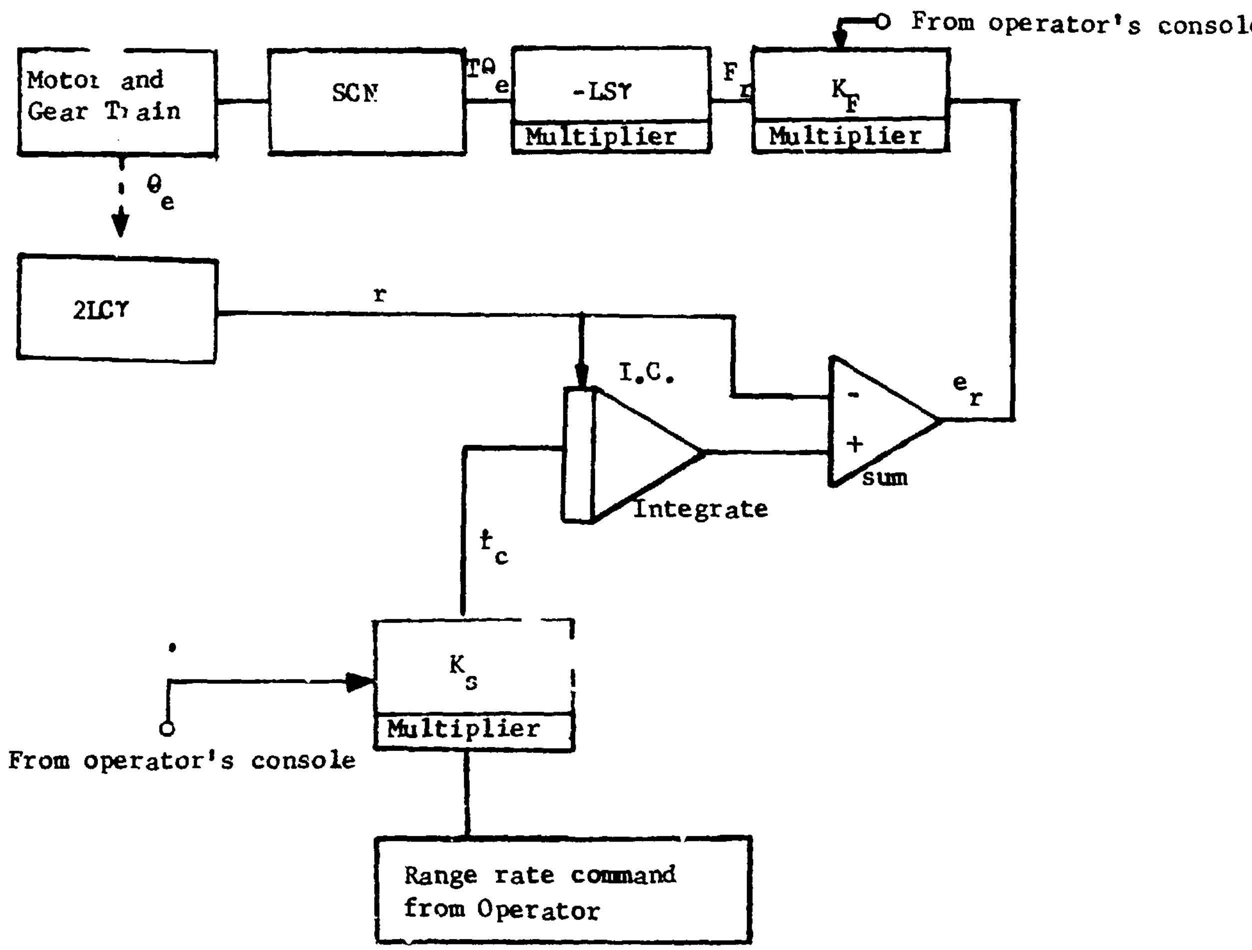


Figure III-6 "Rate-Position" Range Control Loop

a. θ_e = manipulator elbow angular position

b. γ = 1/2 θ_e

c. L = manipulator segment lengths

d. r = length of range vector

e. $\dot{r}_c$ = commanded range rate

f. e_r = range position error signal

g. $C\gamma$ = Cosine (γ)

h. $S\gamma$ - Sine (γ)

i. K_s = controller sensitivity gain

j. K_F = range forward loop gain

k. F_r = derived force to be applied in range direction

l. $T_{\theta e}$ = elbow actuator torque command

m. SCN = servo compensation network

The range rate input command is integrated and compared with the actual arm range length to form a range position error signal. This error is processed identically to the rate error of the "rate-rate" approach. Note the integrator, programmed on an analog computer, is initial conditioned to the range value to prevent servo saturation when the computer is switched from the I.C. to operate mode.

Bilateral Control

Fig. III-7 depicts the gimbal labelling and ordering of the vertical slider bilateral position controller.

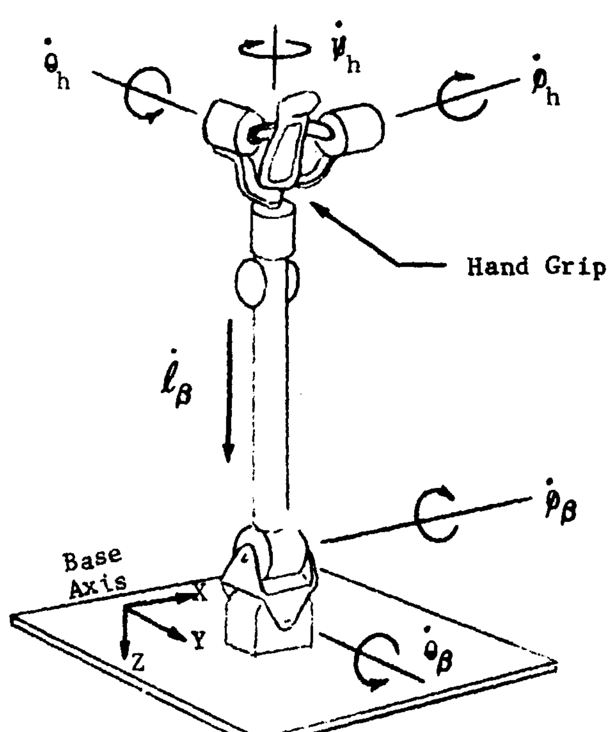


Figure III-7 Bilateral Position Controller

Movement of the base pitch gimbal (θ_β) deflects the hand grip in the X direction which corresponds to a range command. Likewise an azimuth command is associated with movement of the base roll (ϕ_β) and elevation is controlled via the verticle slider ℓ_β. The wrist attitude gimbals ϕ_h, θ_h, and ρ_h are related on a one-to-one basis with the manipulator wrist three degrees of freedom.

1. Range

The bilateral range equations appear in Fig. III-8.

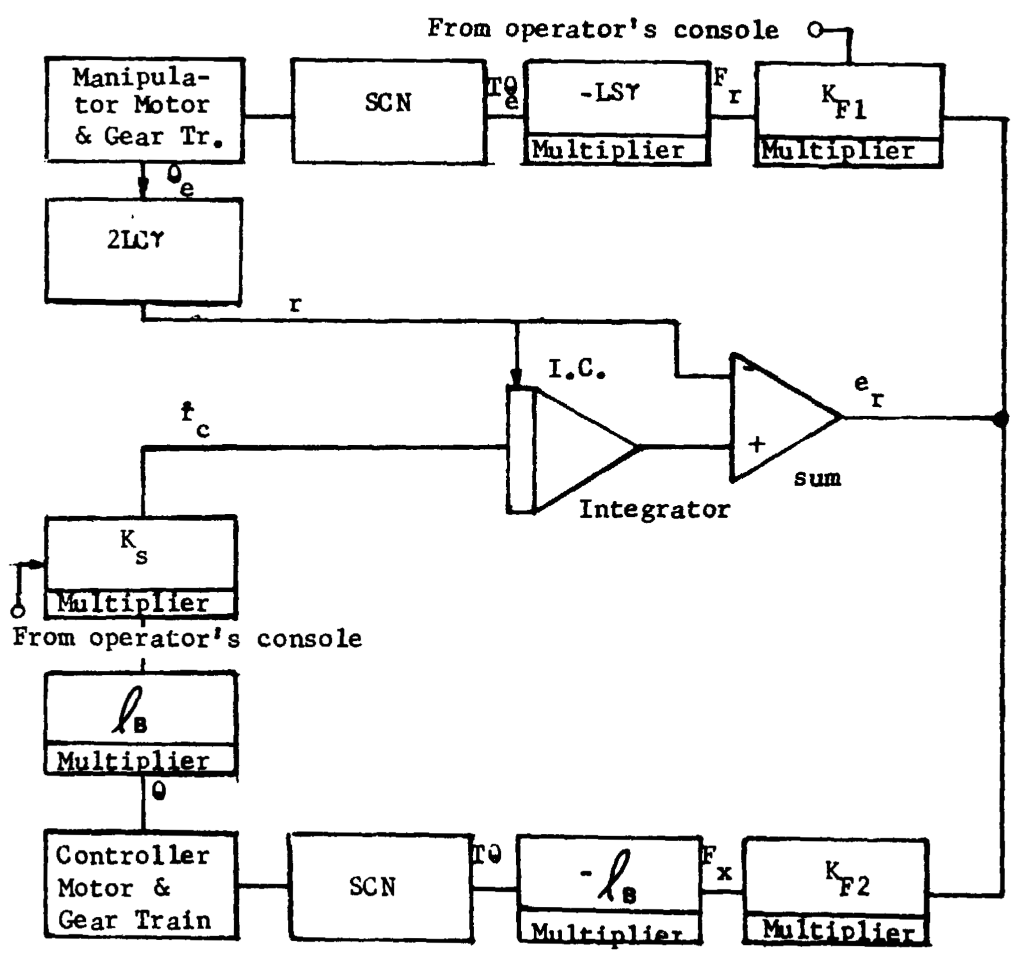


Figure III-8 Bilateral Range Control Loop

a. θ_e = manipulator elbow angular position

b. $\dot{\theta}_\beta$ = controller base pitch gimbal rate

c. r = length of range vector

d. $\dot{r}_c$ = commanded range rate

e. ℓ_β = length of controller vertical height

f. L = manipulator segment lengths

g. γ = $1/2\ \theta_e$

h. $C\gamma$ = Cosine (γ)

i. $S\gamma$ = Sine (γ)

j. K_{F1} = manipulator range forward loop gain

k. K_{F2} = controller X forward loop gain

l. F_r = derived range force to be applied by manipulator

m. $T_{\theta e}$ = elbow torque command

n. F_X = derived X force to be applied by controller to the operator

o. $T_{\theta\beta}$ = controller base pitch joint torque command

p. e_r = range position error signal

q. K_s = controller motion ratio gain

r. SCN = servo compensation network

A range rate command is generated by multiplying the controller base pitch rate by the vertical height of the hand grip and the controller sensitivity gain K_s. This rate is integrated and compared with the actual range position to form a position error signal. The error signal transforms into a manipulator range force and a controller X force by the forward loop gains K_{F1} and K_{F2}, respectively. The manipulator elbow and controller pitch torques are in turn derived by the distribution equations:

1. $T_{\theta e} = (-LS\gamma)\ F_r$
2. $T_{\theta} = (-\ell_\beta)\ F_X$.

The controller to manipulator force reflecting ratio (FRR) is given by:

$$FRR = 1:\frac{K_{F1}}{K_{F2}}.$$

Since K_{F1} is operator variable, the force reflecting ratio is a changeable parameter. The motion ratio (MR) between controller hand grip and manipulator wrist attachment point, given by

$$MR = 1:K_s,$$

is likewise variable since the operator controls the sensitivity gain K_s. Note that the force reflecting and motion ratios are independent in that varying one does not effect the other, and both are invariant to changes in arm geometry.

It might be wondered why a range rate command that must be integrated is formed from controller gimbal rate information instead of directly calculating a position command. To facilitate position indexing, an integrated rate command is desired. By depressing the index button mounted on the hand grip, the integrator input is grounded, and thus no command changes are sent to the manipulator or controller. After completion of the procedure, the index button is released restoring the rate command to the integrator input. This technique requires no indexing equations and results in no transients applied to either controller or manipulator.

2. Azimuth and Elevation

Fig. III-9 and III-10 reveal the bilateral control equations coupling the input controller with the manipulator azimuth and elevation degrees of freedom.

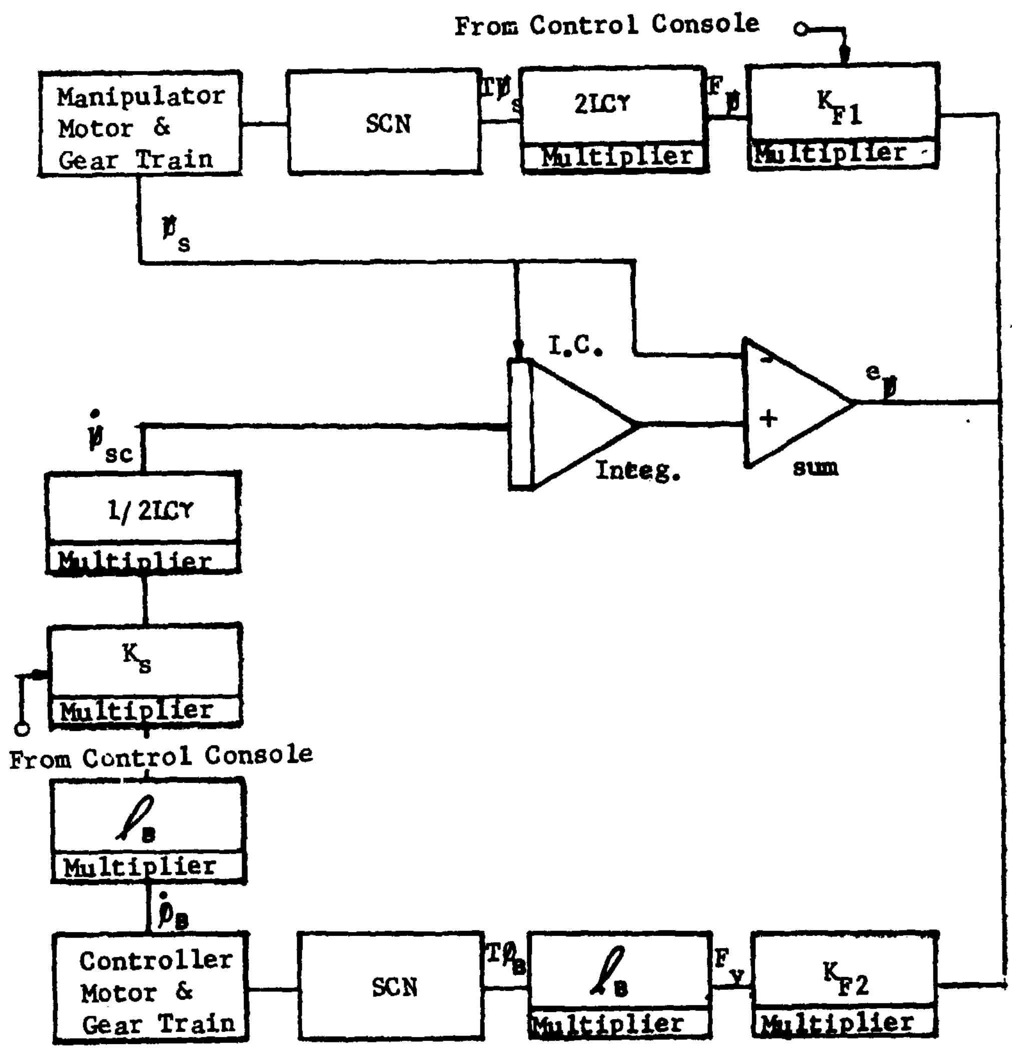


Figure III-9 Bilateral Azimuth Control Loop

a. ϕ_s = manipulator shoulder yaw angular position

b. $\dot{\phi}_{sc}$ = commanded shoulder yaw rate

c. ℓ_β = length of controller vertical height

d. L = manipulator segment lengths

e. γ = $1/2\ \theta_e$

f. $C\gamma$ = Cosine (γ)

g. K_s = controller motion ratio gain

h. K_{F1} = manipulator azimuth forward loop gain

i. K_{F2} = controller Y forward loop gain

j. $\dot{\phi}_{\beta}$ = controller base roll gimbal rate

k. e_{ϕ} = azimuth position error signal

l. F_Y = derived Y force to be applied by the controller to the operator

m. F_{ϕ} = derived azimuth force to be applied by manipulator

n. T_{ϕ_β} = controller base roll joint torque command

o. $T_{\phi s}$ = shoulder yaw torque command

p. SCN = servo compensation network

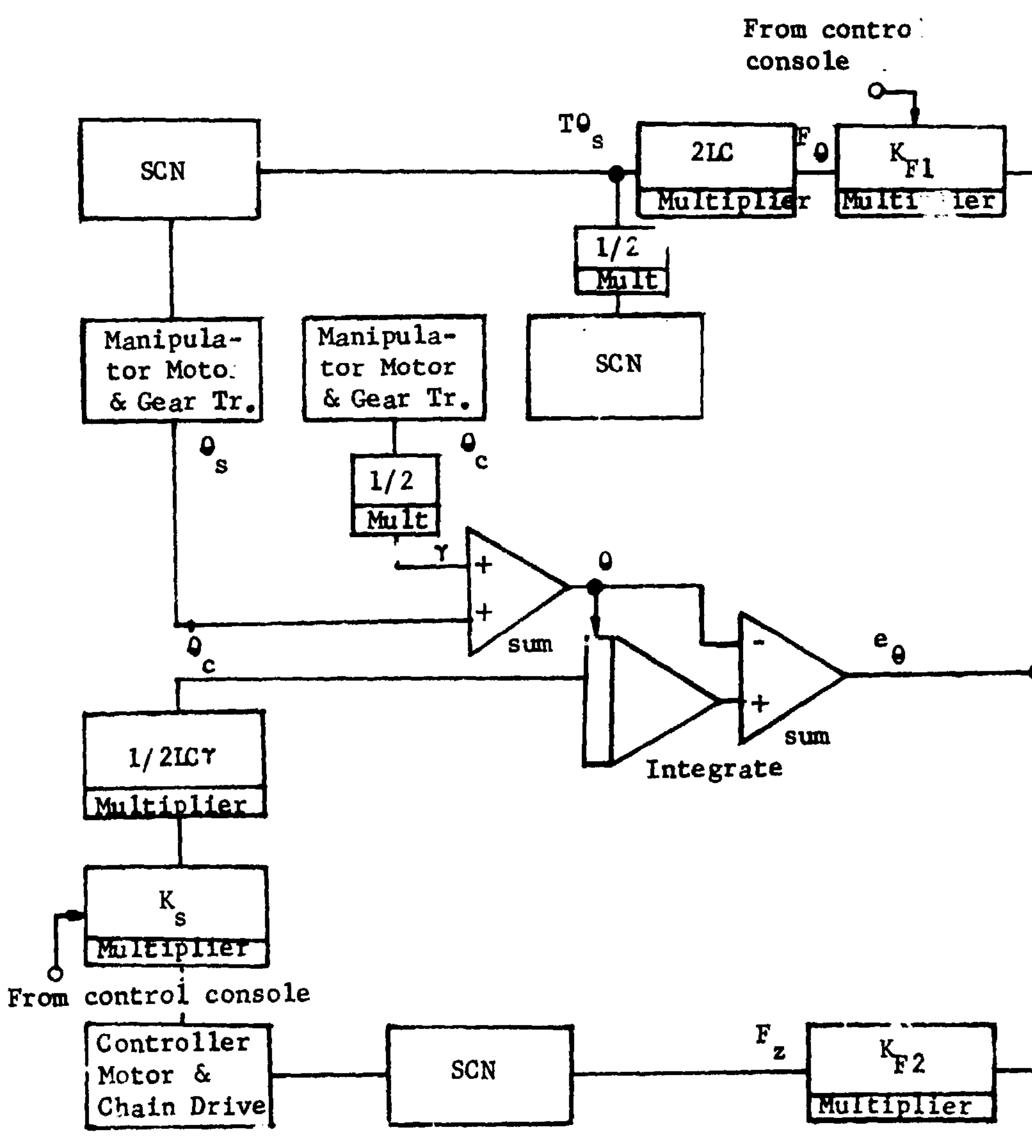


Figure III-10 Bilateral Elevation Control Loop

a. θ_s = manipulator shoulder pitch joint angular position

b. θ_e = manipulator elbow joint angular position

c. γ = $1/2\ \theta_e$

d. ℓ_θ = controller vertical slider linear rate

e. θ = manipulator wrist point elevation angle

f. $C\gamma$ = Cosine (γ)

g. e_θ = elevation position error signal

h. K_s = controller motion ratio gain

i. K_{F1} = manipulator elevation forward loop gain

j. K_{F2} = controller Z forward loop gain

k. F_θ = derived elevation force to be applied by manipulator

l. F_Z = derived Z force to be applied controller to operator

m. $T_{\theta s}$ = shoulder pitch torque command

n. L = manipulator segment lengths

o. $\dot{\theta}_c$ = commanded elevation rate

p. SCN = servo compensation network

The azimuth and elevation bilateral control loops are based on the same philosophy and have identical capabilities (variable FRR and MR) as the range degree of freedom and therefore do not require a written narrative.

4. <u>Wrist Pitch</u>

The control equations coupling the controller and manipulator wrist pitch, yaw and roll degrees of freedom are identical, and therefore only the pitch gimbal is presented, Fig. III-11.

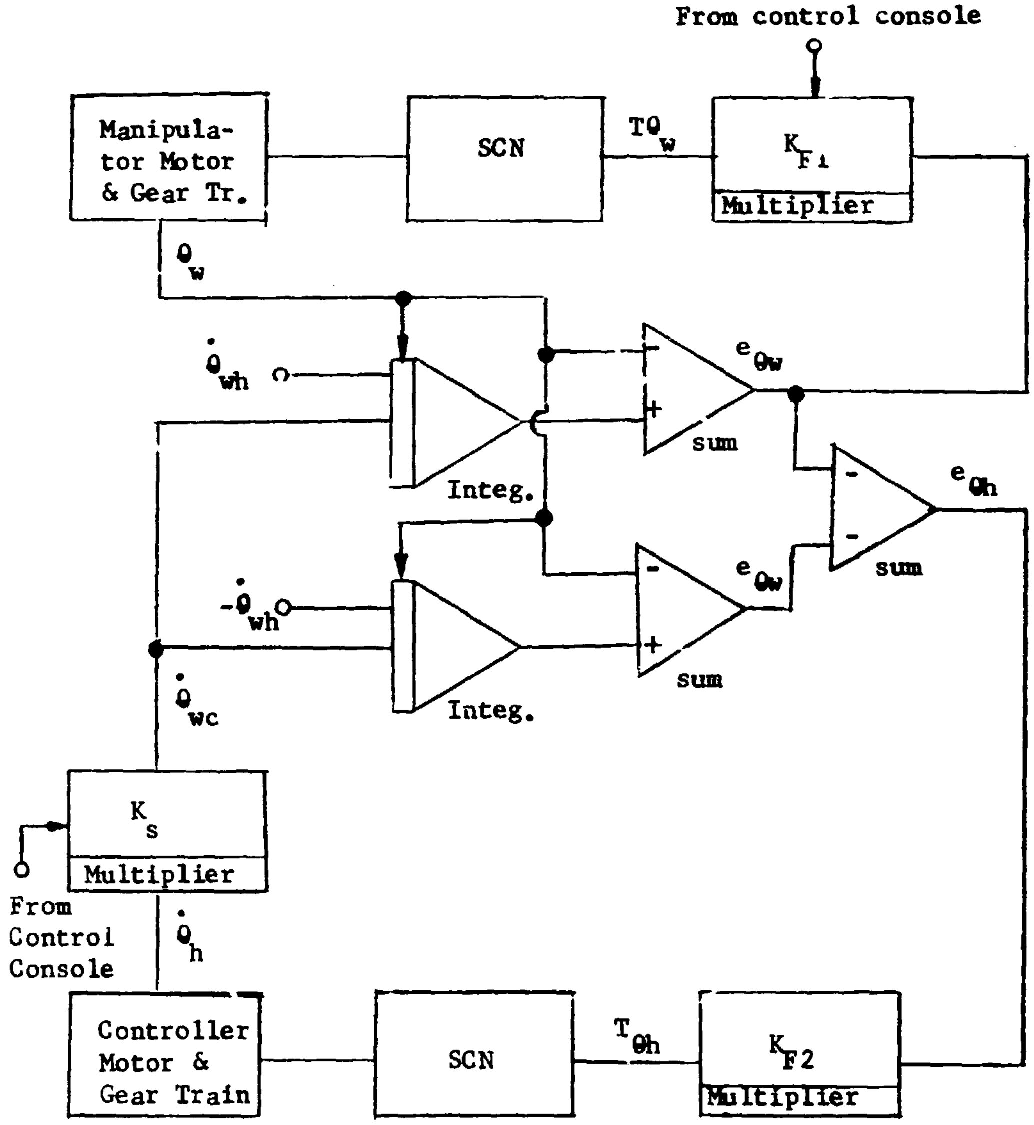


Figure III-11 Bilateral Wrist Pitch Control Loop

a. θ_{ω} = manipulator wrist pitch angular position

b. $\dot{\theta}_{h}$ = controller wrist pitch angular rate

c. $\dot{\theta}_{\omega c}$ = commanded wrist pitch rate

d. $\dot{\theta}_{\omega h}$ = wrist pitch hawk command

e. K_{s} = controller motion ratio gain

f. K_{F1} = manipulator wrist pitch forward loop gain

g. K_{F2} = controller wrist pitch forward loop gain

h. $e_{\theta\omega}$ = wrist pitch position error signal

i. $e_{\theta h}$ = wrist pitch position error signal

j. $T_{\theta\omega}$ = manipulator wrist pitch torque command

k. $T_{\theta h}$ = controller wrist pitch torque command

l. SCN = servo compensation network

Analogous to the translational degrees of freedom, the attitude equations provide variable torque reflecting and motion ratio gains. In contrast to the RAE approach, dual integrators are incorporated to properly process the applied hawk commands. To eliminate the hawk commands from influencing the input controller, two error signals ($e_{\theta\omega}$ and $e_{\theta h}$) are formed, one containing position and hawk information ($e_{\theta\omega}$) and the other possessing only position data ($e_{\theta h}$). With this technique, the bilateral coupling between controller and manipulator is uneffected when the manipulator wrist attitudes are subjected to hawk control.

C. SERVO SYSTEM

1. Servo Considerations

Following the formulation of control law equations, a servo system design must be performed to assure the total manipulator system has the desired operational qualities (i.e., stability, bandwidth, resonant frequency, etc.). The control laws presented in Figs. III-2 through III-11 present a somewhat formidable servo design challenge for numerous reasons - the most troublesome of which are:

a. Varying arm inertias - the inertia reflected to the output shaft of each gimbal actuator is a function of arm geometry. Thus, as the manipulator moves about, the load inertia presented to each joint varies.

b. Varying payload inertia - not only must the manipulator function unloaded, operation with a variety of payloads attached to the end effector is required. This payload variation accentuates the changing inertia problem introduced above.

c. Nonlinear Equations - the control equations contain the sine and cosine of the elbow half angle. These nonlinear functions enter in the joint actuator servo loops, requiring a linearization to be performed before standard linear servo design techniques are useful.

d. Varying loop gains - since the force reflecting and motion ratios for the bilateral controller and the rate and force sensitivity for the unilateral rate controllers are operator selectable parameters, the loop gains associated with these functions likewise must vary. These changing gains affect servo performance and thus influence the design procedure.

Design Technique

To stabilize each gimbal actuator a servo compensation network (SCN) was fabricated to appropriately shift the phase characteristic of the input torque command. To design the SCNs, linearized open loop transfer functions were obtained for each controller (bilateral) and manipulator servo motor. These transfer functions were derived by first considering all loops (determined by the control laws) associated with a particular gimbal, and then linearizing the loop equations to yield the desired function. Since a linearized analysis is valid only for a small region surrounding the linearization point, a nominal arm configuration ($\theta_e = 90°$) was selected to initialize the design procedure. Likewise, midrange values of the variable loop gains (force reflecting and motion ratios) and load inertias were initially used in each transfer function to yield compensating network centered at a "nominal" gain crossover frequency.

The SCNs, of the lead variety, were used to provide large amounts of phase shift of the "nominal" gain crossover frequency (ω_{ngc}). Since a 20° phase margin appears more than adequate to stabilize the joint actuators of a manipulator system subjected to low frequency smoothly varying input commands, a 60° phase margin was placed at ω_{ngc} in the hopes that as the inertia, gains, and arm geometry changed, this stability parameter would not dip below the 20° value. The SCNs were fabricated from active components and featured a programmable design, as will be discussed momentarily.

Manipulator Elbow Gimbal Servo System

Since all servo systems of the controller and manipulator were designed with the same philosophy, only the one applicable to the manipulator elbow is presented to explicitly reveal the technique used. Fig. III-12 represents the transfer function of the elbow a tor and its associated range and elevation feedback loops valid for the bilateral and "rate-position" control modes.

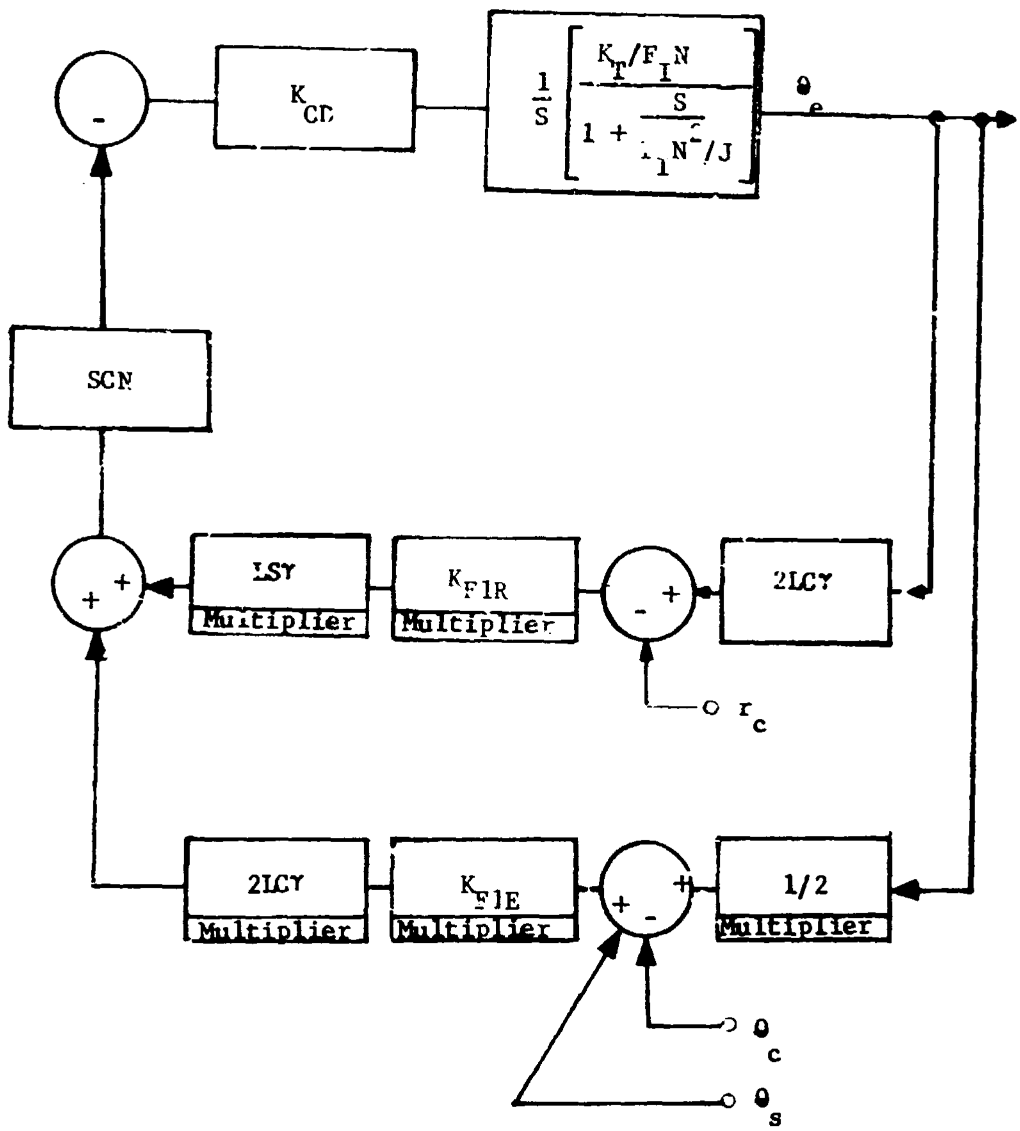


Figure III-12 Manipulator Elbow Servo System

a. K_{CD} = current drive power amp. gain

b. K_T = servo motor torque sensitivity

c. F_I = infinite source impedence damping coefficient

d. N = gear ratio

e. J = actuator assembly and load inertia

f. S = Laplace operator

g. θ_e = elbow angular position

h. γ = $1/2\ \theta_e$

i. $C\gamma$ = Cosine (γ)

j. $S\gamma$ = Sine (γ)

k. L = manipulator segment length

l. K_{F1R} = manipulator range forward loop gain

m. K_{F1E} = manipulator elevation forward loop gain

n. r_c = range position command

o. θ_c = elevation position command

p. θ_s = manipulator shoulder pitch angular position

q. SCN = servo compensation network

Linearizing about a nominal arm geometry, the following substitutions can be made:

$$\boxed{2LC\gamma} \longrightarrow \boxed{K_2\theta_e}$$

$$\boxed{\begin{array}{c} 2LC\gamma \\ \hline \text{MULT} \end{array}} \longrightarrow \boxed{\begin{array}{c} K_3 \\ \hline \text{MULT} \end{array}}$$

$$\boxed{\begin{array}{c} LS\gamma \\ \hline \text{MULT} \end{array}} \longrightarrow \boxed{\begin{array}{c} K_4 \\ \hline \text{MULT} \end{array}}$$

where the K_i are gains determined by arm position. Simplifying, the above figure is reconstructed as shown in Fig. III-13.

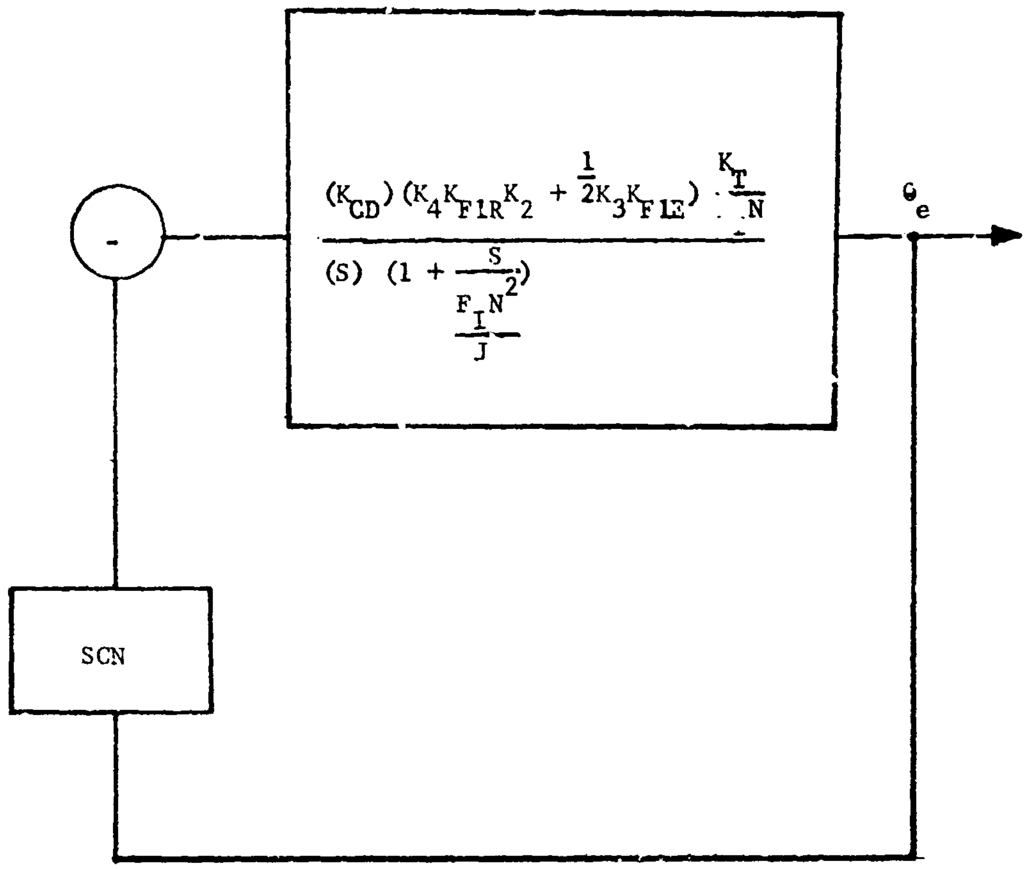


Figure III-13 Linearized Manipulator Elbow Servo System

Substituting midrange values for K_{F1R}, K_{F1E}, and J, the open loop Bode gain and phase curves of the Fig. III-13 transfer function can be plotted to reveal the location and shape of the needed stabilization network.

Servo Compensation Network

As mentioned, the servo compensation networks were of the lead type having the general transfer function

$$G_{SCN} = \frac{1 + S/a}{1 + S/b}, \qquad \text{(III-2)}$$

where a and b are the zero and pole break frequencies, respectively. The filter introduces no dc attenuation and can easily produce 60°

phase shifts. At the time design work was proceeding on the servo system, the SMA hardware was in fabrication. This fact, coupled with several additional unknowns (such as desired range of FRR and MR values) dictated the filter networks be programmable. That is, as the hardware became a reality and desired operational performance became firm, the servo systems could be altered by easily adjusting the SCNs. Fig. III-14 reveals the G_{SCN} realization utilizing operational amplifiers. Potentiometers 1 and 2 provided adjustment of the zero break frequency ($10^{-3} \leq a \leq 10^{2}$) with potentiometer 3 varying the zero-pole separation ($1 \leq b/a \leq 50$).

Although the compensating technique yielded a well stabilized, highly versatile manipulator servo system, the approach is by no means optimum. Troublesome areas that should be corrected preceding additional simulations are:

(1) Lead filters that introduce large amounts of phase shift have positive gain in the high frequency region, thereby accentuating noise problems.
(2) Lead filters generally increase a systems bandwidth. Since the SMA has a low bandwidth requirement ($\leq$ 1 hz), the increased response allowed the electrical time constants of the torque motors to become noticeable. These constants were not included in the servo model and thus unpredictable behavior occurred for large values of b/a.
(3) Large values of FRR and MR could not be achieved. As the K_{Fi} and K_s gains became large, the filter widths were insufficient to assure at least a 20° phase margin, and consequently instabilities occurred.

Hawk Commands

Description - Hawk control refers to the automatic partial or full attitude hold of the manipulator wrist gimbals. With a hawk mode acti-

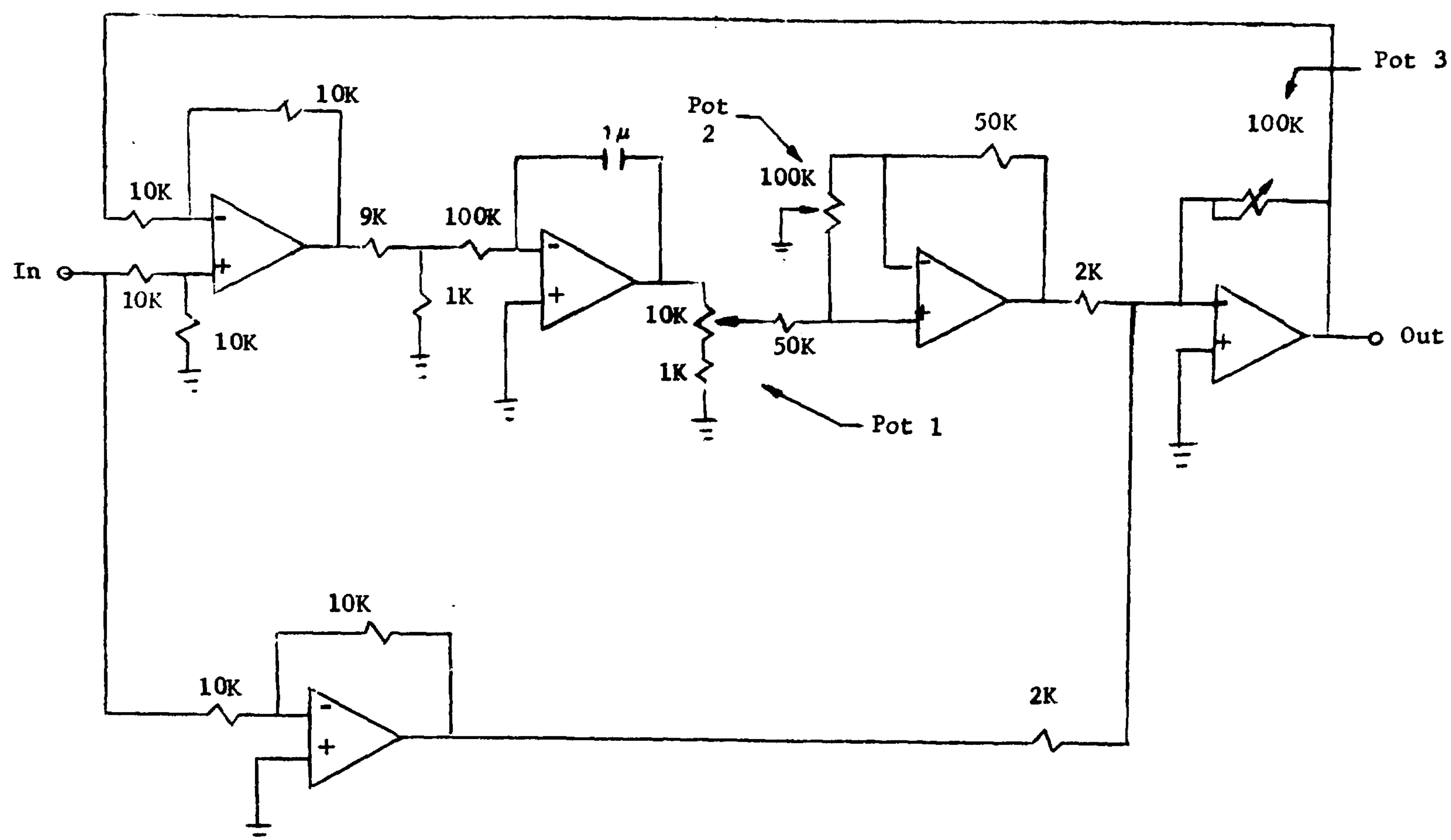
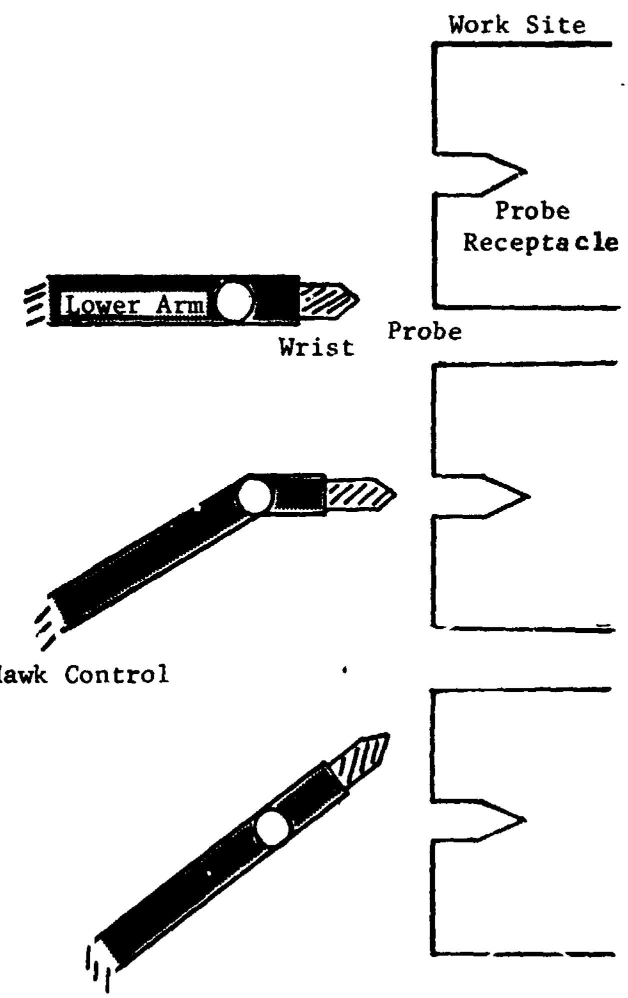


Figure III-14 Servo Compensation Network Realization vated, the operator can translate the manipulator in range, azimuth or elevation and the wrist gimbals will be automatically driven such that the terminal device does not change its original attitude. Fig. III-15 crudely depicts an initial manipulator position with respect to a fixed work site followed by two final positions indicating how the wrist attitude (one DOF shown only) changed with and without hawk control.



a. Initial Position

b. Final Position with Hawk Control

c. Final Position Without Hawk Control

Figure III-15 Wrist Attitude Hawk Control

To implement hawk control, the needed wrist gimbal attitude changes are computed from knowledge of changes in the shoulder and elbow gimbals. The computed values are then summed with the operator commands and applied to the wrist actuators to maintain the TD attitude in the desired position.

Range Hawk - Two types of hawk control were used in the SMA simulation. The first technique, denoted "range hawk", was the simplest of the two methods in that only the wrist pitch was affected. When a range translational command was given, a drive to the wrist pitch was applied to prevent an attitude change. The three wrist commands, Figs. III-5 and III-11, for range hawk are:

$$1.\quad \dot{\theta}_{\omega h} = -\dot{\theta}_{e/2} \qquad \text{(III-3)}$$

$$2.\quad \dot{\phi}_{\omega h} = 0$$

$$3.\quad \dot{\rho}_{\omega h} = 0.$$

Full Hawk - The second method was a "full hawk" in that all three wrist gimbals were driven to prevent an attitude change occurring from a range, azimuth, or elevation translational motion. The three hawk commands were determined by computing the TD body rates, given the shoulder and elbow gimbal rates, and then deriving wrist gimbal rates from these body rate values. Fig. III-16 defines the axis systems used in the calculations, with the following equation revealing the three wrist hawk commands.

$$\begin{bmatrix} \dot{\rho}_{\omega h} \\ \dot{\theta}_{\omega h} \\ \dot{\phi}_{\omega h} \end{bmatrix} = -D_{\epsilon 3} D_{23} \left[\begin{bmatrix} 0 \\ \dot{\theta}_e \\ 0 \end{bmatrix} + D_{12} D_{\epsilon 1}^{-1} \begin{bmatrix} 0 \\ \dot{\theta}_s \\ \dot{\phi}_s \end{bmatrix} \right], \qquad \text{(III-4)}$$

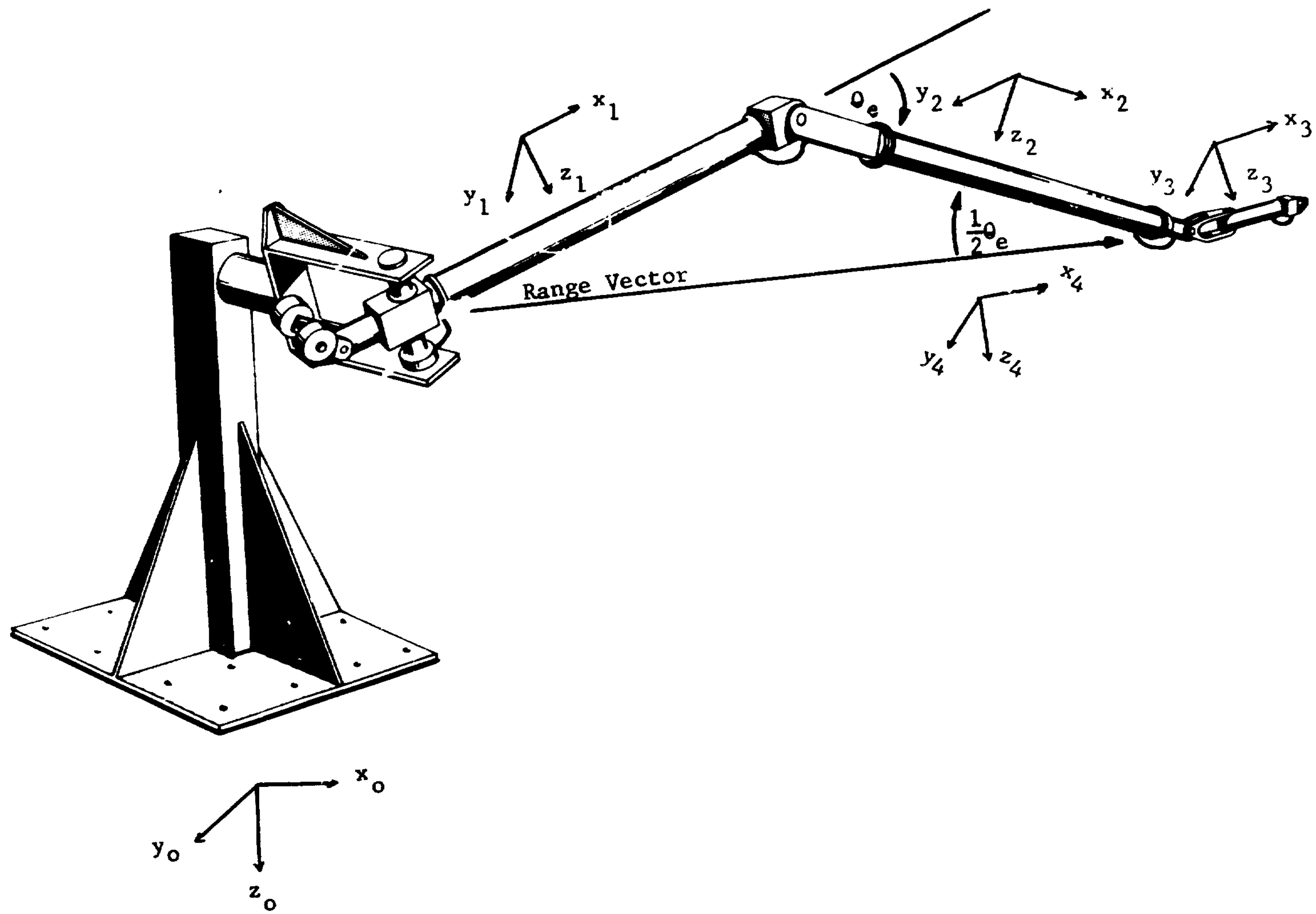


Figure III-16 SMA Coordinate System Nomenclature where

D_{ij} = Euler angle coordinate transformation from i^{th} to j^{th} coordinate system.

$D^{-1}_{\epsilon 1}$ = Euler rate transformation from shoulder pitch and yaw gimbal rates to axis system 1 body rates.

$D_{\epsilon 3}$ = Euler rate transformation from axis system 3 body rates to wrist gimbal rates.

Substituting the D transformations into III-4 yields,

$$1.\quad \dot{\rho}_{\omega h} = \frac{S\theta_1 \dot{\phi}_s}{C\phi_\omega} \qquad \text{(III-5)}$$

$$2.\quad \dot{\theta}_{\omega h} = -\dot{\theta}_e - \dot{\theta}_s - T\phi_\omega S\theta_1 \dot{\phi}_s$$

$$3.\quad \dot{\phi}_{\omega h} = -C\theta_1 \dot{\phi}_s,$$

where

a. $\theta_1 = \theta_e + \theta_s + \theta_\omega$ (III-6)

b. $S\theta_1$ = Sine (θ_1)

c. $C\theta_1$ = Cosine (θ_1)

d. $C\phi_\omega$ = Cosine (ϕ_ω)

e. $T\phi_\omega$ = Tangent (ϕ_ω).

Additional Desired Transformation

It was observed in the evaluation of the various range, azimuth, elevation control modes that insertion or retraction of a probe (or module) in a pure X, Y, or Z direction presented moderate difficulties. If the capability had been provided to issue commands in the TD axis system (#3 system of Fig. III-16), pure XYZ motion (referenced to the #3 axis system) would have been easily accomplished. The needed transformation

$$\begin{bmatrix} R \\ A \\ E \end{bmatrix} = D_{24} \, D_{32} \left[\underline{X}_{C3}\right] \qquad \text{(III-7)}$$

relates commands ($\underline{X}_{C3}$) given in axis system 3 to the appropriate RAE values in axis system 4 (the range vector). Substituting for the D_{ij} yields

$$\begin{bmatrix} R \\ A \\ E \end{bmatrix} = \begin{bmatrix} C(\theta_\omega + \gamma)C\phi_\omega & -C(\theta_\omega + \gamma)S\phi_\omega & S(\theta_\omega + \gamma) \\ S\phi_\omega & C\phi_\omega & 0 \\ -S(\theta_\omega + \gamma)C\phi_\omega & S(\theta_\omega + \gamma)S\phi_\omega & C(\theta_\omega + \gamma) \end{bmatrix} \left[\underline{X}_{C3}\right], \qquad \text{(III-8)}$$

where $\gamma = 1/2\ \theta_e$.

Noted, that to achieve the desired TD cartesian motion, the above transformation must be used in conjunction with the "full hawk" mode.

When XYZ control of the manipulator tip is desired, the question arises as to relative complexity between:

(1) A spherical base system with full hawk and a TD to range vector transformation, and
(2) A cartesian base system with full hawk.

It is believed, although not yet proven, that the spherical approach simplifies the problem, for no Jacobian inversion is required.

IV. Simulation Description

All control of the slave arm for accomplishing the simulation tasks was conducted from the operator's control console using the TV images and other displays. Input commands from the rate or position controllers were sent to the analog computer which then calculated the torque commands to each of the SMA joints according to the control laws discussed in Section III. Actual arm motion was then picked up by the TV cameras, sent to the console monitors, and used by the operator to determine his next input command. The operator could pan, tilt, or zoom as desired to improve his motion perception ability. Arm joint angles and commanded forces and torques were also displayed to the operator and used, if required to determine his next command.

A considerable amount of knowledge and information about system operational characteristics was learned during the system checkout phase and initial familiarization period. Much of this understanding is subjective in nature and as such may not necessarily be supported by the recorded simulation data. This information however will be reflected in the conclusions presented in Section V. The initial familiarization period also was used to establish desirable ranges of operating conditions, such as motion ratios, force and torque ratios, and rate gains, which were used during the data recording period. The specific values of these variables used during a run were recorded on data sheets. Recommendations as to parameter values for future use are presented in Section V.

Simulation Tasks - Each operator was required to accomplish very specific tasks using the various capabilities designed into the task panel. These tasks are described in the following:

A. From a specified initial position of the SMA, translate to and attempt to align the terminal device with the fixed 8" long bar. The initial misaligned arm position was defined by the following wrist angles, pitch = 50°, yaw = -30°, and roll = -30°, and a tip position approximately 3 ft to the right, 2 ft down and 1 ft in front of the fixed bar. After angular alignment data was taken, the operator was instructed to grab the bar, and apply a pure X force, then a pure Y force, and then a pure Z force (no translation involved).

B. After attaching to the square translational friction rod, attempt to pull the rod out and then push it in (X translational motion) while keeping side loads on the rod (Y and Z directions) to a minimum. This rod was held by a friction device such that it could only slide in the X direction and with a push/pull force of approximately 3.5 lbs.

C. After attaching to the rotational bar, attempt to rotate the bar about its hinge point through 90° with minimum X, Y, or Z forces applied to the task panel. This bar was attached to the task panel through a friction device which required 1.5 ft-lbs of torque to rotate.

D. With 8" long, 1/4" diam. pin in grip of end effector, initially align the pin with the large 1-1/4" diam. receptacle. After taking angular alignment data, attempt to insert and retract the pin in the receptacle while minimizing side (Y and Z) forces.

E. With 8" long, 1/4" diam. pin in grip of end effector, initially align the pin with the small 1/2" diam. receptacle. After taking angular alignment data, attempt to insert and retract the pin in the receptacle while minimizing side (Y and Z) forces.

These tasks are those for which task time and force and moment data were recorded. Due to time limitations it was not possible to ta data on other tasks designed into the task panel.

Data and Results Discussion - A summary of the task time data for each of the tasks and control alternatives, and for the three operators is shown in Table IV-1. Where no task times are shown, either the task was not done or no time was taken because the task or task times were not considered important.

Angular alignment data was recorded for several of the tasks to determine how well the operator could align the TD perpendicular to the task panel. No angular alignment aids were used, and it was expected that alignments would not necessarily be good. The angular misalignments were allowed, and were even desirable, because a goal of the simulations was to assess how well the different control systems could tolerate the angular misalignments. Certainly these misalignments made the tasks much more difficult, and it is recommended that in actual manipulator system use, an angular alignment aid be utilized to initially align the TD with the tank panel very accurately. Generally, the operator could align the TD in roll and yaw to within approximately 5° and 10° respectively. The pitch DOF seemed to present more of a problem and was generally misaligned by 25°.

In the following, each task is discussed separately, and samples of the recorded data are shown.

Task A, Static Application of Pure X, Y, and Z Force - Both the unilateral rate and bilateral position techniques demonstrated the ability of a range, azimuth, elevation control scheme to apply pure X, Y and Z forces (referenced to the task panel). The force application technique utilized for both controller types was primarily the same--apply a force in the R, A, or E direction roughly corresponding to the desired X, Y, or Z direction then systematically null out unwanted forces and moments (revealed by meter display)

TABLE IV-1

TASK TIME DATA
FOR ALL TASKS AND OPERATORS
TIME IN SECONDS

Task		Operator 1			Operator 2			Operator 3	
		R-P	R-R	BIL	R-P	R-R	BIL	R-P	R-R
A		108			165			107	
B	Out	90	130	25	39	25	148	80	15
	In	98	49	12	85	45	45		15
C		85	9	5	50	10	9	37	3
D	In	21		150	52			73	60
	Out	17		15	23			135	10
E	In	55	45	50	170	59	95	38	230
	Out	35	29	15	16	10	15	49	15

as they developed while continuing the pressure in the primary direction. The bilateral controller presented minor difficulties by coupling the desired force with the other degrees of freedom--although if care and patience were taken, the task could consistently be accomplished. Figure IV-1 depicts force application with the rate rate system and reveals the consistency between control law derived and load cell measured applied forces.

Task B, Friction Rod Retraction and Insertion - Friction rod motion was one of the more difficult tasks to consistently complete. Small forces and torques applied in the off-motion direction would bind the rod such that extremely large forces were needed to produce any motion at all. Operation with the rate controllers produced consistent task completion, although run times were often excessive resulting from a "stop and think" period followed by trial and error commands to dislodge the rod. Contrary to intuition, bilateral control seemed to complicate the task at times, yet perform superbly on other runs. If precisely the proper forces and torques were applied to the bilateral controller, the rod would insert and retract smoothly with one clean motion. If the rod began to bind, often the situation became unsalvageable due to coupling between all controller degrees of freedom. As noticed in a previous bilateral simulation ("Two DOF Large Payload Handling Simulation," R73-48664-003) decoding the force information fed back to operator's hand was at times impossible. Also previously noted, visual feedback tends to be dominant in that the force information is often ignored or disbelieved if the eye does not reveal the problem being indicated to the hand.

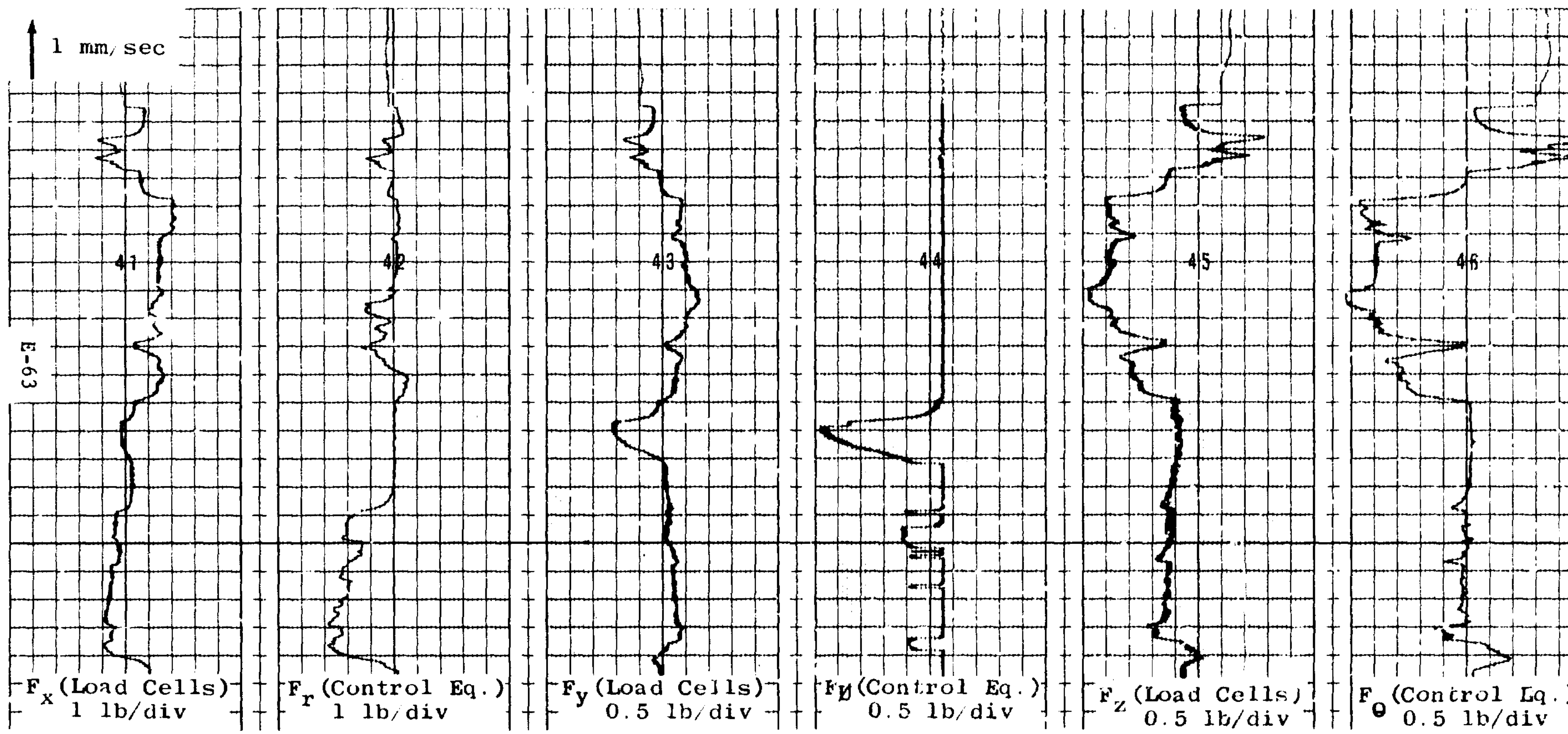


Figure IV-1 Task A. Rate-Rate Applied Translational Forces

Task C, Bar Rotation - At the simulation onset, bar rotation was the one task believed unachievable with a unilateral rate system. At the simulation conclusion, bar rotation was the discovery key to a rate technique allowing any force related task to be accomplished. Initially, the task was attempted with the rate controllers by applying a slow wrist roll command followed by carefully nulling out the unwanted forces that developed as the bar rotated. Likewise, with the bilateral controller, a wrist roll was applied and the controller was allowed to "track along" by loosely holding the hand grip. Amazingly, both systems accomplished the rotation, although the bilateral was far superior. Upon reasoning why bilateral control was so easy, it became apparent the "track along" capability of the bilateral scheme was the answer. The "follow" nature of the input controller to slave motion prevented any unwanted forces from developing. Attempting to incorporate this feature for the unilateral rate mode, the translational DOF servo stiffnesses were set to zero allowing the shoulder and elbow gimbals to freely backdrive. Now when a wrist roll command was given, the bar easily rotated and the manipulator "tagged along for the ride". The task was accomplished in mere seconds with minimum development of undesired forces and torques.

Tasks D & E, Probe Insertion - Inserting the small probe in the large diameter receptacle presented no difficulties for either the unilateral or bilateral system. The clearance tolerance was so large the probe would never bind regardless of the misalignment error magnitudes. Probe insertion in small diameter receptacle, on the other hand, was the most difficult of all attempted tasks. The probe would easily bind, producing the identical problem as encountered with the friction rod. Task completion could often not be achieved with the bilateral controller if the initial alignment errors were large. Although consistent success with rate control was achieved, task times were large when the pin became jammed. It was learned the "free gimbal" techniques greatly aided the rate control. Once the probe tip was successfully mated with the receptacle, the servo stiffness of the altitude gimbal was set to zero, allowing the wrist to self-align with the hole. Once aligned, the proper RAE commands were more easily achieved to finalize probe insertion.

V. Conclusions and Recommendations

Control Law Discussion

1. Rate-Position System - A characteristic of this system is that forces and torques applied to or by the arm can be held after the controllers have been returned to null. This means that a force build-up in a direction not desired must be nulled by controller commands. Since the applied forces and moments were known and were displayed to the operator, he could readily and quite accurately null these unwanted forces. To accomplish the tasks with this system, the operator would build up forces in the direction required, while continuing to null forces in the other directions. This continued nulling procedure did consume a large portion of the total task time.

The primary problem with the rate-position system was the inherent ability to build up error signals which could become larger than the level corresponding to maximum force capability of the arm. If this occurred, it was necessary to apply a command to reduce this error signal to where a force change could be detected. During this time the operator had no indication of exactly what was happening and it became relatively easy to lose control of the arm, i.e. not knowing immediately what to do to regain control. This problem however could be avoided by introducing logic into the control equations such that the error signal could not continue to build up after it reached a maximum level. With this addition, the rate-position system should work relatively well for the tasks attempted.

2. Rate-Rate System - A characteristic of this control system is that for a fixed task panel forces and torques applied to or by the arm

can be held only by maintaining a controller deflection, i.e. when controller deflections are nulled, all forces on the arm will quickly go to zero (within joint backdrive friction levels). The arm joints must be backdriveable, as the SMA joints are, for this to occur. This characteristic was judged to be very desirable since it was no longer necessary to actively null forces or torques in unwanted directions. In effect they were nulled automatically. Furthermore, the time required to automatically null unwanted forces was variable by controlling the rate loop gain. High gains made the system capable of supporting forces for long periods while zero gains meant that no forces can be supported.

Comparison: Rate-position vs Rate-Rate - The inherent variable backdriveability of the rate-rate system is considered a great advantage in accomplishing the tasks as far as both time and ease of doing the tasks are concerned. A similar effect can be obtained in the rate-position system by lowering loop gains (in this case system compliance is changed), however, the inherent requirement of eventual position correspondence of integrated commands and actual tip position negates the desirable effect. For both systems, the displayed forces and torques, which are very necessary for doing service or maintenance tasks in order to know what is happening, were judged to be very easy to use for control. Their use however was required much less for the rate-rate system than the rate-position system.

3. Bilateral Position System - The primary characteristic inherent in the bilateral system is that forces and torques applied to or by the arm are felt directly by the operator's hand. Forces on the arm can be

sustained only if an opposite force is applied to the controller. Although the bilateral system was operating well and all tasks could be accomplished, there were several problems which presented difficulties to the operator. One of the major problems was the cross-coupling between forces and torques. Wrist torques are developed whenever forces are applied and forces develop whenever torques are applied. In a situation where all forces and torques are acting simultaneously, which was true of almost all tasks, it was difficult for the operator to quickly discern, from what he felt in his hand, what his next command should be. The problem was particularly bothersome for the task of inserting the small pin in the small receptacle.

Another problem that was bothersome to the operator concerned the controller itself and was due to the fact the controller was not counterbalanced when displaced in the X and Y directions. The forces the operator felt from the non-counterbalance degraded his ability to detect forces fed back from the slave. During operation this problem was intentionally minimized by using the controller at or near its most upright position (which probably increased the number of required indexes). It is believed, however, that the basic conclusion drawn from the simulation would not change if this problem were corrected.

The bilateral system also seems to be a much more fatiguing mode of operation than the rate systems. Besides tiring the arm, the hand muscles also become fatigued due to the tight gripping force required to firmly hold the controller grip. Furthermore, the position controller must continuously be held for long periods of time, if several tasks are to be accomplished, in order to always maintain slave control. In other words, the position system does not allow any "hands off" type of operation. Using the rate system, the operator can let go of the controls, relax, and take time to study a problem before inputting another command. The position controller must always be held. This generally leads to more mental fatigue with the position system as well as physical fatigue.

4. Unilateral Position System - The unilateral position system, where no forces are sent back to the controller, was determined to be the most difficult mode of operation. No data was taken using this system. To perform tasks with the unilateral system, it was necessary to use the force and moment information displayed on the meters. It was determined that much better control of the applied forces could be obtained using the 2, 3-DOF rate controllers than the single 6-DOF position controller.

Comparison: Rate-Rate vs Bilateral Position - The simulation data shows that in general the operator could perform the tasks faster and better with the rate-rate system than with the bilateral system. All operators definitely preferred the rate-rate system and agreed that this system in general required less training, was less mentally and physically fatiguing, gave much smoother control, and presented much less cross-coupling problems (particularly when using the rate-rate system variable backdriving capability) than the bilateral system.

Discussion of Other Simulation Parameters

1. Hawk Mode - Although not thoroughly investigated during the simulations, the Hawk mode, or automatic terminal device attitude hold mode, was determined to be a valuable control law. If the attitude of the TD could be initially aligned pendicular to the task panel face, which could be easily accomplished with a simple alignment aid, the (full) Hawk mode would assure that translations of the TD anywhere across the panel would not produce any angular misalignments. Many tasks should be able to be accomplished without further manual attitude inputs. For gross translations of the arm, the (Range) Hawk mode would assure that no attitude changes of the TD, and attached payload, if any, would occur relative to the operators view from the base TV camera.

2. Automatic TV camera Tracking of TD Tip - This feature which is very easily implemented, was judged to be very desirable for gross motions of the TD. For tasks where only small arm motion and a small field-of-view are required, automatic TV tracking was felt to be undesirable. The recommended implementation is the same as used in the simulation, namely a auto track on/off switch with manual pan/tilt control always available. A feature not available in the simulation was a variable rate manual pan/tilt control. It is recommended that this be added, especially for cameras adjustments when viewing close-in (small FOV). A continuous rate variation is not required, possibly only on high, medium, or low setting.

3. Control Axis Considerations - For general operation on gross translational motion of the arm, motion correspondence between actual and commanded

motion direction has always been considered almost mandatory for good control. The spherical reference axis system used for the control laws has inherent coordinated control if the tip is viewed from a camera located at the arm shoulder. In reality of course the camera could not be placed at this position because of mechanical and visual interference. The best camera location seemed to be at shoulder height but approximately 5 ft to either side of the arm base. This gave a sufficiently clear view of the work area and TD, and did not affect coordinated motion to the extent that was bothersome to the operator. For the orientation of the task panel relative to the arm used in the simulation, the wrist rotational motions were also sufficiently coordinated with wrist commands such that no particular control problems were noted by any of the operators. It is likely that this is true independent of task panel orientation, so long as the operator can see the wrist gimbal axes. This should be proven however in future simulations.

Although it was determined that the control laws, especially the rate-rate system, are tolerant of large angular misalignments between TD and task panel and of translational commands not parallel or perpendicular to the task panel (for say the pin insertion task), it is recommended that a TD control axis capability be added to the control laws for translational motion and used along with the hawk mode. Much of the difficulty of doing the tasks was due to the fact that the spherical control laws gave for an X command a translational motion not perpendicular to the task panel face. Thus where a pin is being pulled out by an X command, motions in Y and Z relative to the task panel fixed axis also occurred. This problem can easily be corrected by using the TD control axis, which would result in translational motions parallel and perpendicular to the panel face (assuming the TD was perpendicular to the face to begin with). This added control feature, which requires only one two-axis transformation to implement (See Eq. III-8, Page III-33), should improve the performance of certain tasks considerably.

4. TV Camera Location - The TV camera located offset from the manipulator base provided tolerable visual coverage of the task panel. End effector alignment was difficult for the probe-receptacle mating task as the camera angle did not provide good alignment cues. Familiarization with manipulator operation and with the visual scene did tend to minimize viewing deficiencies. A terminal device mounted camera would be a boon to delicate manipulation and to end effector alignment preceding a grasp, insert, or retract motion. While operating with a terminal device camera, control in the TD axis system would be required and easily achieved with the addition of the #3 to #4 axis system transformation (Equation III-8).

5. Position Indexing - Position indexing the bilateral controller functioned exceeding well. The controller could easily be relocated by depressing the index button with no discontinuities occurring at the controller or manipulator when the index button was released. It was revealed, as initially believed, the indexing function is essential to a nongeometric controller possessing variable motion ratio capability.

6. Control Console Displays - The gimbal angle readouts were, for all practical purposes, useless. The operator was not concerned with actual joint angles and, consequently, seldom glanced at the meters. To the contrary, the force and moment readouts were essential to the rate control, and to some extent were also needed for the bilateral system. Desired force application with the rate system was simply achieved by monitoring the force meters.

Insertion and retraction of the friction bar and small probe were often accomplished with the bilateral controller only after inspecting the force and moment meters to discover where the unwanted pressure was occurring.

The dial calibrations for the force reflecting and motion ratios, as well as the rate controller sensitivities, were beneficial in providing the familiar operator an easy "set-up" procedure at the beginning of each task. Also, mid-run adjustments were quickly made by a mere glance at the control panel.

The zoom lens readout provided the precise focal length, in millimeters, of the adjustable camera lens. Although of no great benefit for monoral viewing, the stereo display was synchronized by setting the zoom to 64MM, thereby matching the fixed 64MM focal length of the other stereo camera.

Recommended Control Technique

From the information gained in the SMA simulation, present knowledge indicates the rate-rate RAE/Rotation control technique to be the most versatile and simpliest to implement of the three schemes considered. Inclusion of the full hawk and TD to range vector transformation equations yields a system capable of operating in spherical base and cartesian terminal device coordinates.

The following eight evaluation areas were considered in the determination of the preferred control technique:

1. Motion Coupling - For tasks requiring stringent separation of translational and rotational motion (probe insertion being one example), rate control proved superior. It was difficult to purely translate without rotations with the bilateral controller due to rotational gimbals coupling the hand grip with the translational degrees of freedom.

2. Force Coupling - Contrary to the initial belief that bilateral control would precisely inform the operator of applied forces and moments, it was often difficult to usefully decode the force and moment information supplied the operator via the hand grip. To exemplify, when a module would bind in the process of insertion, the binding moment could not be accurately resolved from the desired forces and moments.

3. Motion Sensitivity - Using a "quick pulse" technique on the input controllers, the rate system consistently yielded minimum motion of 1/16 inch. Although 1/16 inch motion could also be obtained with the bilateral controller, there was little consistency in the ability to repeat the motion. The rate system yielded extremely smooth motion for both gross and fine maneuvers whereas small motions with the bilateral system were somewhat erratic due to the operator's inability to supply minute commands.

4. Force Sensitivity - The sensitivity of the visual force feedback supplied by the force and moment meter displays exceeded the mechanical force feedback of the bilateral controller. Thus precise force application was achieved equally well with both control techniques - providing the bilateral operator relied upon the meter displays to indicate initial force application.

5. Mental and Physical Requirements - The operator mental requirements were comparable for both control schemes. By maneuvering, or flying, the manipulator wrist position, as both techniques did, the operator easily achieved any desired motion. One noticeable difference occurred when the operator attempted to null all arm motion immediately preceding a fine maneuver (probe insertion) to allow an assessment of final alignment.

During this "stop and think time", the bilateral system continuously transmitted residual arm motion through the active controller to the manipulator, thus causing unwanted drift.

Physically, the bilateral controller proved to be quite tiring for long duration tasks. Although gravity was responsible for a portion of the fatique, continued application of all desired forces and torque proved to be annoyingly exhausting. For maneuvers requiring moderate to large amounts of force application with high precision, the physical aspect of the task appeared to become dominant and mental mistakes, such as attitude misalignment, frequently occurred.

6. Servo System Flexibility - The rate system was definitely superior in relation to servo system flexibility. Whereas servo considerations limited the range of achievable motion and force reflecting ratios for the bilateral controller, variable servo stiffness associated with the rate approach permitted free gimbal motion facilitating self-alignment and free tracking. The rate system was easily servo compensated by a versatile technique that allowed large gain and inertia changes. Although the bilateral system did accept large inertia loading, as any bilateral system will, stability sensitivity to large gain changes was apparent.

7. Task Times - No dominant task time advantage was provided by either approach. Although isolated cases of both extremely long and short task times were recorded for both control schemes, the overall time averages were approximately equal.

8. Training Time - Surprisingly, the training time needed to yield comfortable operation was longer for the bilateral controller. No explanation

for this phenomenon is provided for no solid reasons have yet been agreed upon. It is also not clear at this time whether "training time" is even a valid criteria for comparison - and thus no more than this passing mention is provided.

Parameter Value Recommendation

For the selected rate-rate RAE/Rotation control mode, following are recommended parameter values. These values are based primarily on operator choice and reflect the extremes of comfortable operating conditions.

1. Translation controller sensitivity:
   a. Max. = 1 ft/sec.
   b. Min. = 0 ft/sec.
2. Rotation controller sensitivity:
   a. Max. = 8^o/sec.
   b. Min. = 0^o/sec.
3. Servo Stiffness:
   a. Max. = 15×10^3 ft lbs/rad/sec (shoulder)
      8×10^3 ft lbs/rad/sec (elbow)
      2×10^3 ft lbs/rad/sec (wrist)
   b. Min. = 0 ft lbs/rad/sec. (all)
4. Zoom:
   a. Max. = 100MM
   b. Min. = 20MM
5. Force warning indicator:
   a. 70% of max. force or torque
6. Visual display:
   a. Mono - Essential
   b. Stereo - Helpful for fine alignment; to be determined if actually essential.