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Executive Summary

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

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EXECUTIVE SUMMARY

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

Prepared by:

J. R. Tewell
Program Manager

MARTIN MARIETTA CORPORATION
Denver Division
Denver, Colorado 80201

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.

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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 second 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-16. 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 I	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 Posi- tions
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 × 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	$\leq$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	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 summarizes 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

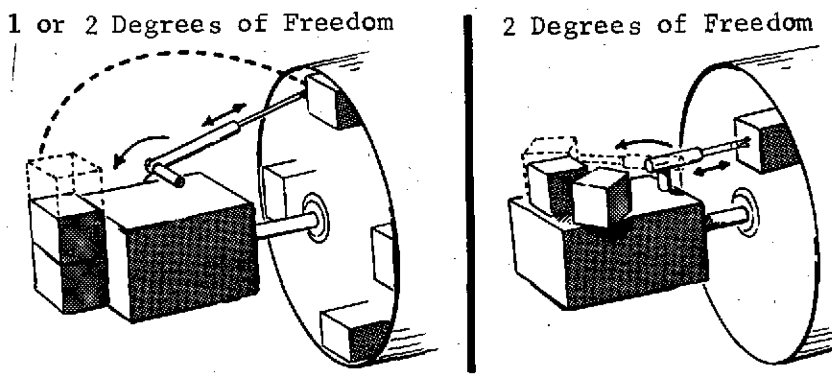
Configuration concepts were divided into two categories, a General Purpose manipulator for satellite servicing applications and a Retrieval Type manipulator for satellite retrieval.

1. General Purpose

General purpose manipulator concepts were developed with complexity ranging from a simple one degree-of-freedom (DOF) device to concepts incorporating more than six degrees-of-freedom, as illustrated in Fig. IV-1.

2. Retrieval Type

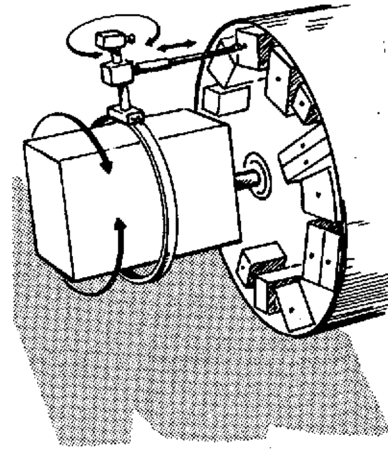
Retrieval manipulator concepts were generated, again ranging from simple to complex devices. As shown in Fig. IV-2, the retrieval device can be a simple docking type device applicable to stable or spinning satellite retrieval or an articulated manipulator for retrieval of spinning/nutating satellites.



a) *Minimum-Degree-of-Freedom Servicing Mechanism*

ADVANTAGES
SIMPLE MECHANISM
SIMPLE CONTROL
LIGHTWEIGHT

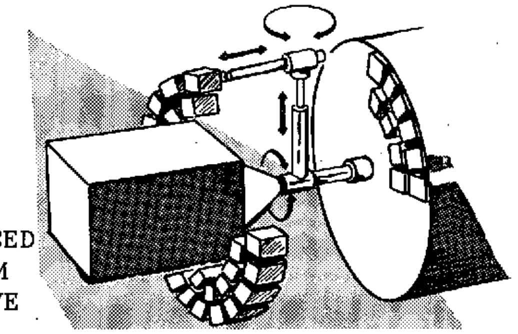
DISADVANTAGES
ONE SURFACE SERVICED
FLEXIBLE MECHANISM
TOLERANCE SENSITIVE



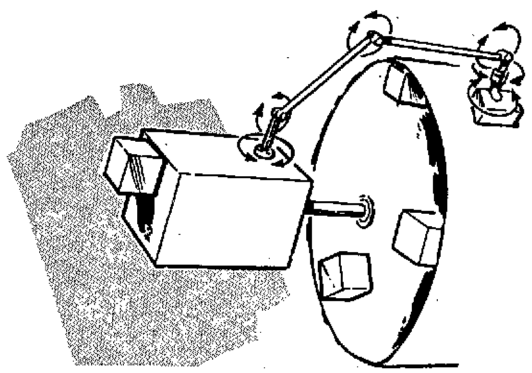
b) *Circular Track with Turret*

ADVANTAGES
SIMPLE MECHANISM
SIMPLE CONTROL
LIGHTWEIGHT

DISADVANTAGES
ONE SURFACE SERVICED
FLEXIBLE MECHANISM
TOLERANCE SENSITIVE



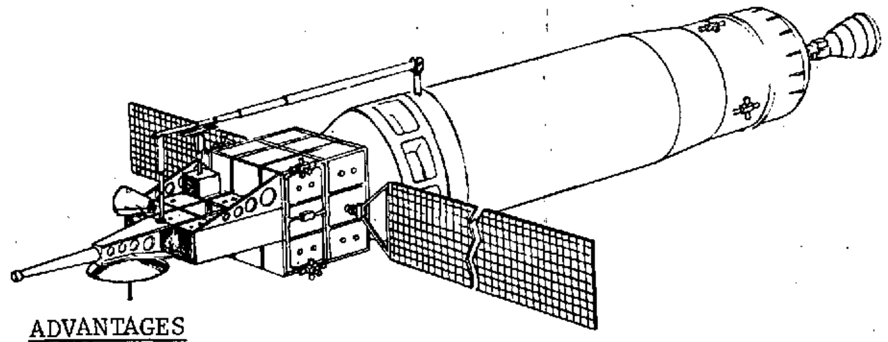
c) *Cylindrical coordinates, Servicing Mechanism, 4-DOF*



ADVANTAGES
MULTIPLE SURFACES SERVICED
MEDIUM WEIGHT
TOLERANCE INSENSITIVE

DISADVANTAGES
COMPLEX CONTROL
COMPLEX MECHANISM
FLEXIBLE MECHANISM

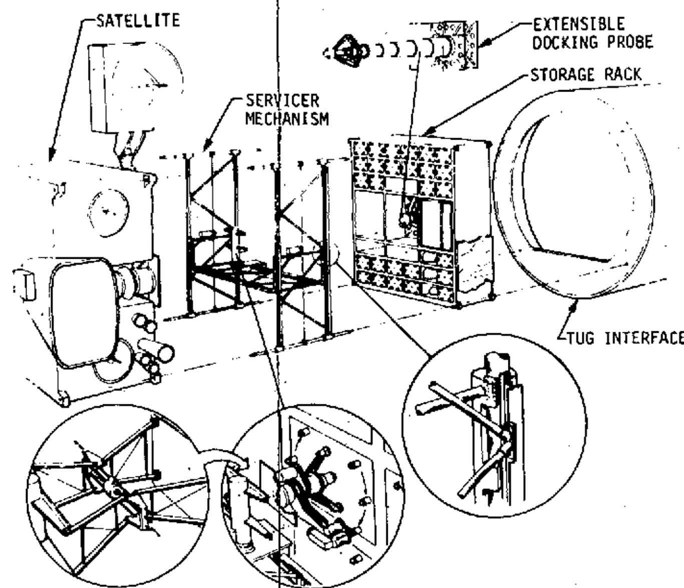
d) *Full-Motion Servicing Mechanism, 6-DOF*



ADVANTAGES
SIMPLE CONTROL
MEDIUM WEIGHT

DISADVANTAGES
COMPLEX MECHANISM
ONE SURFACE SERVICED
FLEXIBLE MECHANISM
TOLERANCE SENSITIVE

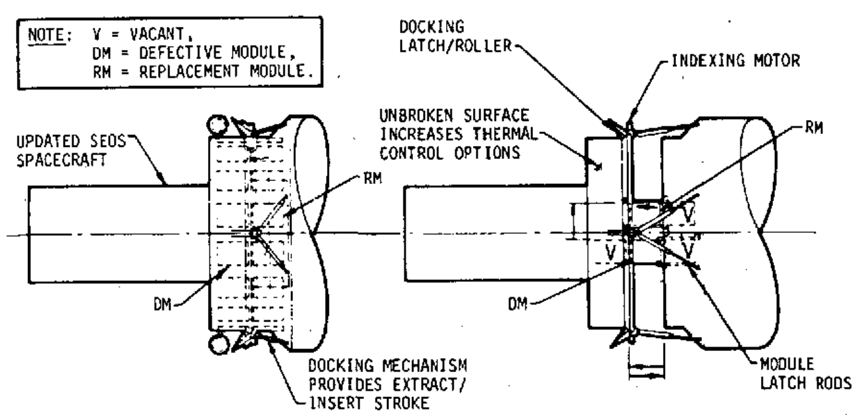
e) *AGOES Being Serviced*



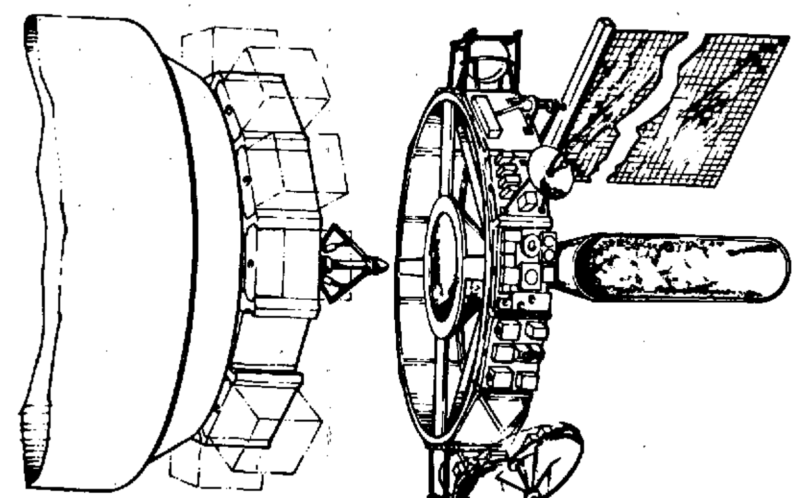
ADVANTAGES
RIGID MECHANISM
SIMPLE CONTROL

DISADVANTAGES
ONE SURFACE SERVICED
COMPLEX MECHANISM
HEAVY
TOLERANCE SENSITIVE

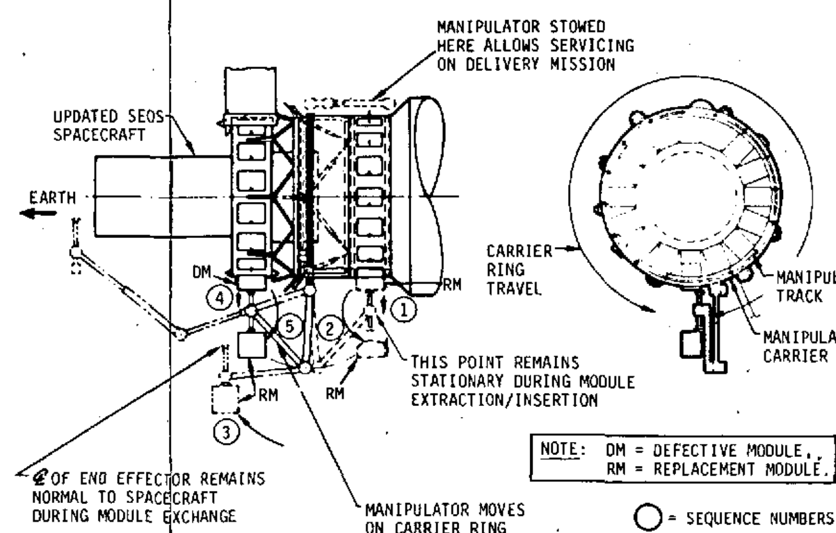
f) *Bell Aerospace Cartesian Coordinates, Servicing Mechanism*



g) *Direct-Access Servicer*

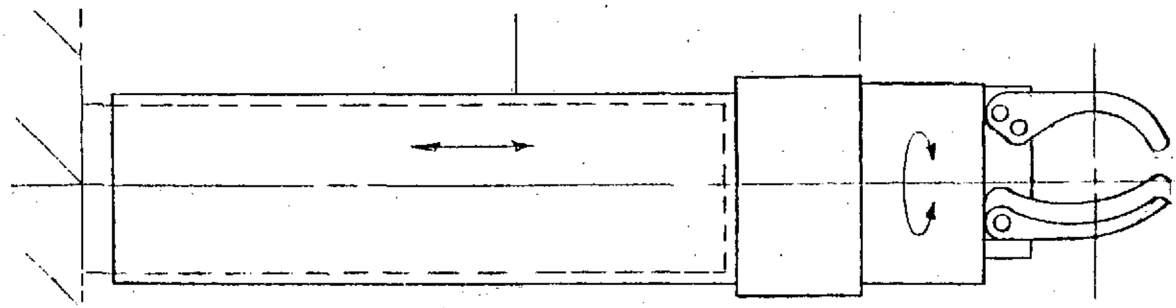


h) *Space Servicing Concept*

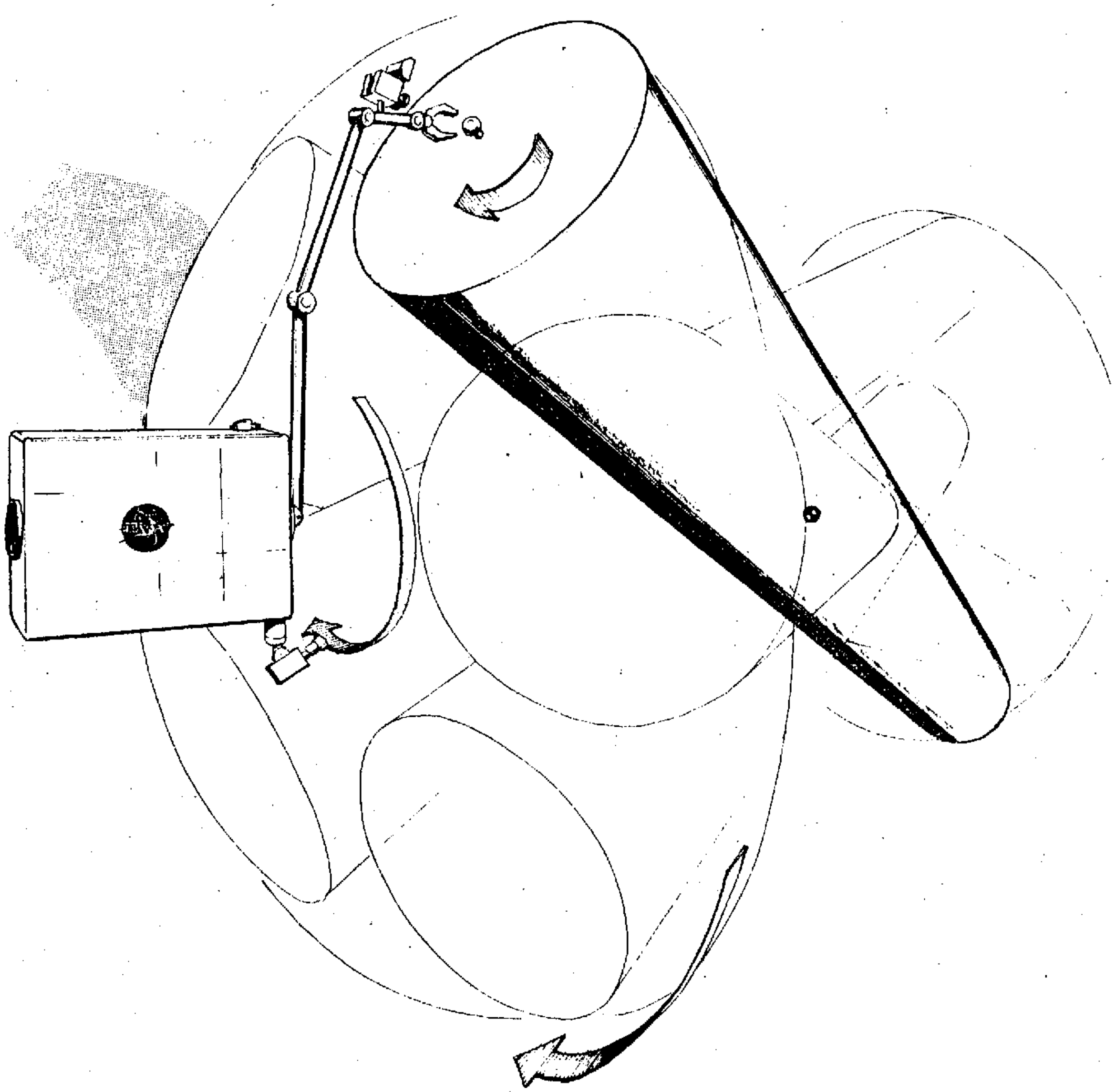


i) *External Manipulator Servicer*

Figure IV-1 General Purpose Servicing Concepts



Stable/Spinning Satellite Retrieval Device



Spinning/Nutating Satellite Retrieval Manipulator

Figure IV-2 Retrieval Manipulator Concepts

3. Manipulator Configuration Summary

It was established that simple mechanisms which 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 retrieval manipulator was found to be essentially a special case of the general purpose manipulator. As shown in Table IV-1, 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 the FFTS 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 as shown in Table IV-2.

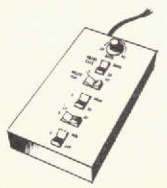
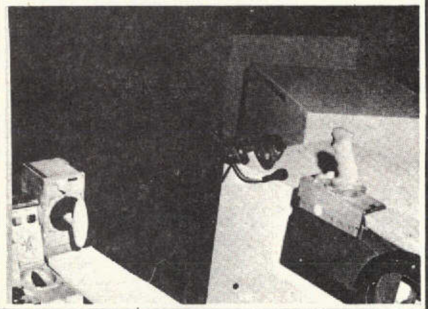
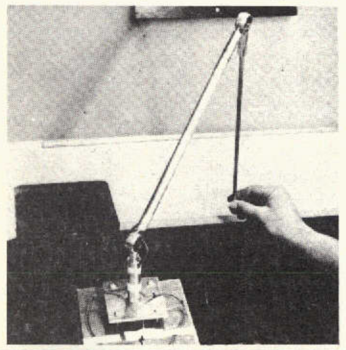
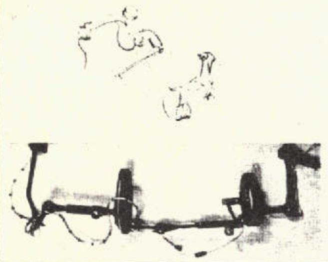
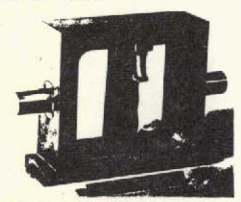
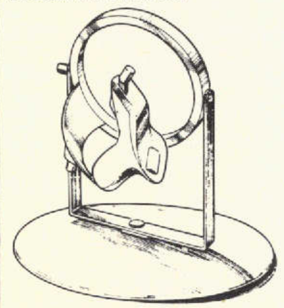
In general, the controllers control either the position or rate of the manipulator. However, one controller, the terminal pointer, is used in a hybrid fashion, i.e. controlling the end effector location in a rate mode while the end effector attitude is controlled in a position mode.

Table IV-1 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)

Table IV-2 Controller Summary

CONTROL DEVICES	DESCRIPTION	ADVANTAGES	DISADVANTAGES
Switch(es)/Potentiometers 	Several levels of switch control exist. The simplest form has a switch for each manipulator joint actuator that controls that actuator at a predetermined or selectable rate in either the positive or negative direction. Another switch control concept employs three switches for X, Y, Z translation of the manipulator wrist and three switches for wrist attitude commands.	Simplicity Uses minimum volume Minimum computer logic	No force feedback Controllability Excessive operator workload Coordinated tip motion difficult to perform
3-DOF Joysticks 	Typically utilizes two 3-DOF Apollo-type controllers. The end effector of the manipulator is "flown" as though it were a free-flyer and there is no direct interaction between the controllers and the manipulator joints. The right-hand controller commands attitude changes of the manipulator wrist and the left-hand controller commands translational motion of the end effector. In general, both controllers are the proportional type in which the commanded angular or translational velocity of the manipulator is proportional to the displacement of the controller grip, up to the manipulator's maximum velocity.	Small operating volume Controller sharing (FFTS & manipulator) No crosscoupling Small input capability	No force feedback Coordinated tip motion difficult to perform Computational complexity
Position (Unilateral and Bilateral) Geometrically Similar Replica 	This concept is one in which the controller configuration is identical to the manipulator configuration in all aspects with the exception of length, which can be scaled to meet the control station volumetric requirements or operator reach envelope. Shown is a photograph of the Martin Marietta replica controller.	Control electronics can be reduced to minimum	Controller volume Limited indexing capability Leads to peculiar operator arm position Controllability
Nongeometrically Similar 	This type of controller concept bears no physical resemblance to the manipulator. In general it overcomes the disadvantages associated with the replica type at the expense of additional control electronics in that it can be configured to meet the task requirements and can include indexing capabilities and control gain ratios as required. A typical Martin Marietta nongeometrically similar position controller (vertical slider) is shown.	Configured to meet task requirements Indexing Variable gain ratios	Large computational requirements Coordinated tip motion difficult to perform
Exoskeleton 	An exoskeleton controller is a mechanism that attaches to the operator's arm and generally has 6 DOF or more. This controller is another form of a position controller that can be configured in either a unilateral or bilateral mode and can be operated in either a replica or nonreplica manner, depending on the manipulator configuration. The figure shows a Martin Marietta space-qualified exoskeleton device used on the Skylab T013 experiment.	Control inputs for more than 6 DOF	Operator's arm is completely dedicated Inadvertent command inputs Large operating volume Human arm limitations
Isometric 	MIT has developed a controller concept for application to manipulator control in which miniature force transducers are used to provide 6-DOF command signals in a single isometric hand controller. Although this unit is basically nonforce feedback, feedback concepts are being analyzed. Presently opinions vary as to the desirability of using a single 6-DOF controller.	Small operating volume Control sharing Small input capability	Coordinated tip motion difficult to perform Tracking task difficult No position or rate feedback Crosscoupling Computational complexity
Terminal Pointer 	This control concept, proposed by URS/Matrix, uses a 3-DOF position hand controller to orient the manipulator end effector and then translate (forward or reverse) in the direction the end effector is pointed is commanded using a proportional rate control signal. End effector grip control is incorporated using a forefinger-actuated position control. The terminal pointer control method allows spatial correspondence between the hand controller and the manipulator tip at all times, negating the requirement for the operator to make mental transformations of coordinate axes.	Separation of attitude & translational commands Indexing Variable gain ratios Capable of controlling two manipulators	Restricted simultaneous motions at the tip Tracking task difficult Leads to peculiar wrist positions
Foot Controllers 	Although foot controllers have generally not been mentioned in the literature for controlling manipulators, they deserve consideration due to the large number of FFTS functions the operator must control. For example, foot controllers are particularly applicable for camera zoom or for camera pan/tilt control and may be used in conjunction with other controller as demonstrated by in-house manipulator simulations. Foot controllers designed and built by Martin Marietta are being used on Skylab Experiment T020, Foot-Controlled Maneuvering Unit, in which foot motions are used to control the astronaut's position and attitude.	Additional control method frees hands for other functions	Operator training Simultaneous arm/hand/foot motion No force feedback Inadvertent inputs

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-3 and the recommended controller types, based upon the application are shown in Fig. IV-4.

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-3 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-4 Controller Recommendations

C. CONTROL MODE CONCEPTS

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 were reviewed. The methods ranged from the extremely simple, yet not so versatile, to the highly complex and dexterous. Rate, position, unilateral and bilateral force reflecting techniques were included in the FFTS control mode candidates which are briefly summarized below.

1. Switch Joint Control

The simplest 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. The control technique is simple. However, 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, 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.

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. Again, both unilateral rate and bilateral position controllers are applicable for XYZ/Rotation control.

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.

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 second technique 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.

6. 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. 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.

7. 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 either a position or rate control input device. Force information is not 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.

8. Control Mode-System Impact

Table IV-3 relates, in a heuristic manner, the impact of the various control modes on the manipulator system parameters. 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.

D. END EFFECTOR CONCEPTS

The primary emphasis during this part of the analysis was to investigate

Table IV-3 Control Mode Impact on System Parameters

Control Techniques	On-Off Joint	Unilateral: Proportional Rate: XYZ/ Rotation	Unilateral: Proportional Rate: RAE/ Rotation	Unilateral: Proportional Rate: Resolved Rate	Unilateral: Proportional Position: Replica	Unilateral: Proportional Position: XYZ/ Rotation	Unilateral: Proportional Position: RAE Rotation	Unilateral: Proportional Position: Resolved Motion	Bilateral: Proportional Position: Replica	Bilateral: Proportional Position: XYZ/ Rotation	Bilateral: Proportional Position: RAE/ Rotation	Bilateral: Proportional Position: Resolved Motion	Inner Loop Force Feedback	Computer Control
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 basic functions of the end effector, such as engage, hold and release and then apply them to a range of feasible mechanisms which could perform the functions. The evaluation considered jaw configurations, handles/or grippers, power or gear train links, and operating characteristics.

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 these three techniques in greater detail in order to assign a preferred priority. Figure IV-5 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) common hand tools have been developed which interface with the parallel jaw type end effector. The alternate selection was the insert and lock concept (I-4). This selection was chosen based on: (1) design simplicity and lightweight and (2) ease of aligning this device with the capture handle.

Parallel configurations conceived for general purpose manipulator application are presented in Fig. IV-6, along with preliminary comparisons of system characteristics.

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.

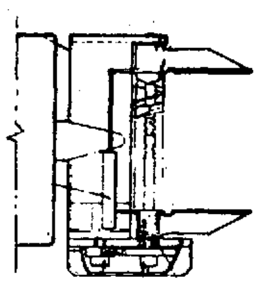
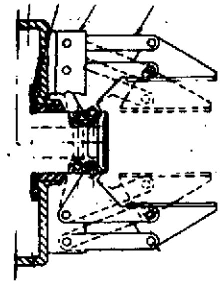
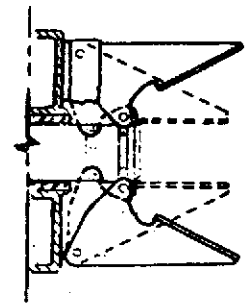
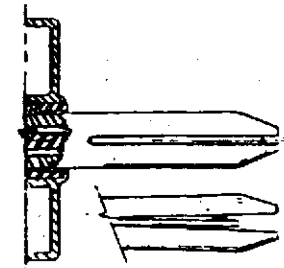
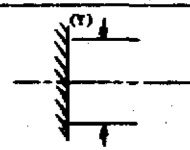
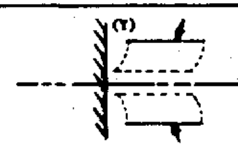
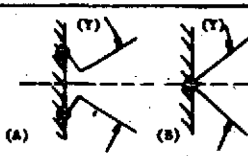
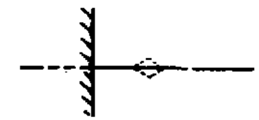
Grip Technique (Artist Concept) / Motion Linkage Parameters	 I-1	 I-2	 I-3	 I-4
1. Basic Jaw Grip Motions				
2. Motion Description	Parallel Vise Where the grip contact point remains stationary.	Parallel motion to the X-axis with a translational arc of ± displacement.	Scissor Motion developed from either 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 then 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-5 Projected Linkage Motions Comparison

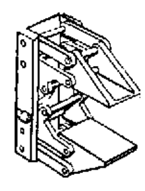
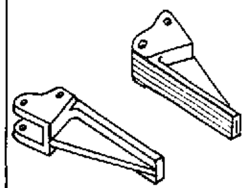
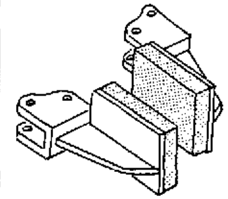
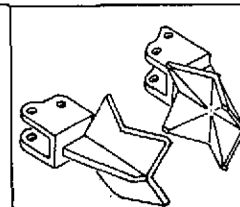
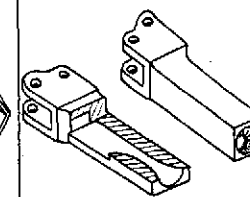
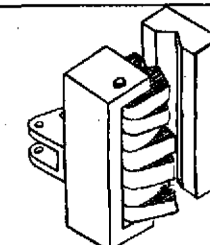
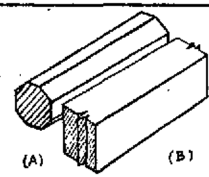
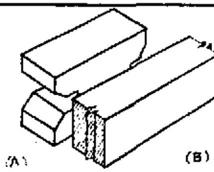
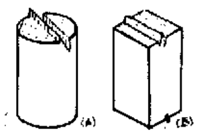
Concepts / Characteristics	 I-1 Parallel/Vise	 I-2 Standard Flat Face	 I-3 Resilent Material	 I-4 Trailer Hitch	 I-5 TKA Jaw Concept	 I-6 Segmented Vise
1. Compatible Handles	 	 	 		Hold Service Tools: ; Any tool with parallel flat surfaces. ; Any tool requiring a common pivot point scissors action; (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 Blaise 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 Flexibility	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 jaws provides capability to grip irregular shapes.	The ball allows large angular misalignment in capture procedures. Special 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-6 Parallel/Vise Concepts Comparisons

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, illustrated in Fig. IV-7, was baselined to incorporate the baseline requirements shown in Table IV-4.

A second concept, previously shown in Fig. IV-1(c) and requiring only four degrees of articulation, was selected as an alternate candidate to be further investigated by the NASA.

Both 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. 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.

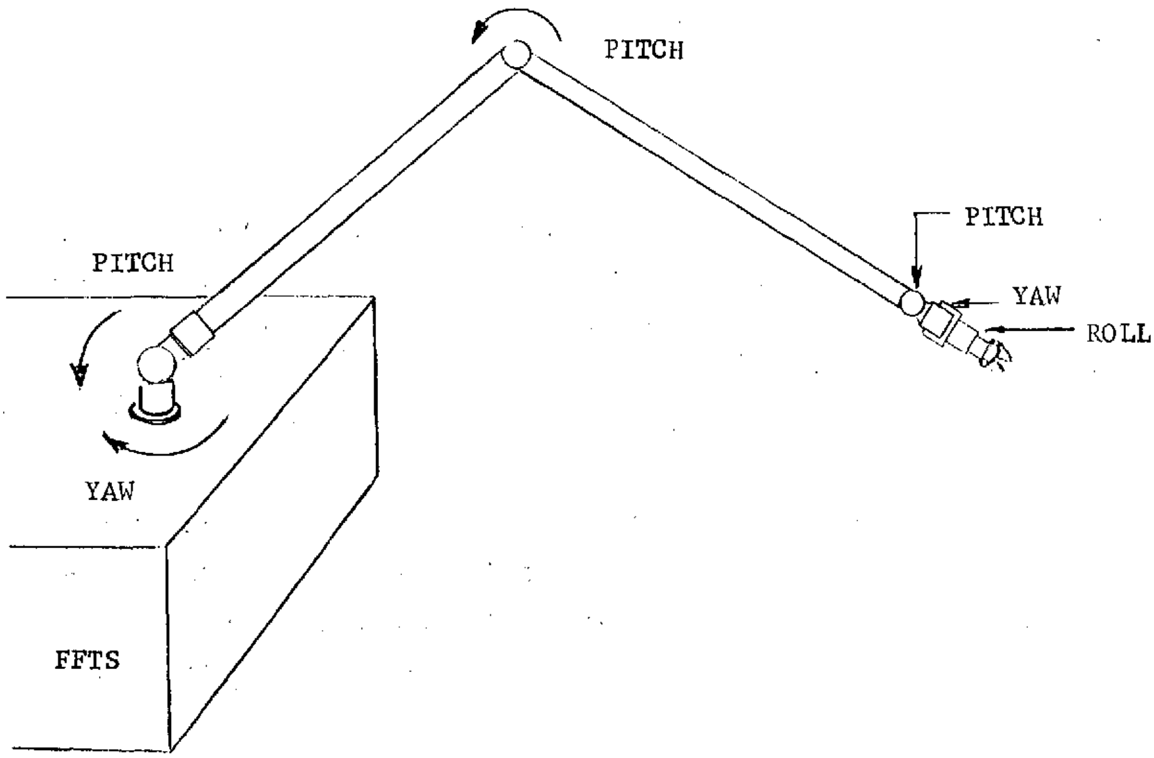


Figure IV-7 Preferred 6 DOF Manipulator Concept

Table IV-4 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: 0.6 m/sec (2 ft/sec)
Mass	$\leq$ 45.4 Kg (100 lbs)

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, 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.

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, summarized in Tables V-1 and V-2, were used to form the framework for the overall design.

Table V-1 Detailed Manipulator Requirements

	Shoulder Yaw	Shoulder Pitch	Elbow Pitch	Wrist Pitch	Wrist Yaw	Wrist Roll
Joint Angular Travel, deg	± 200	0 to +180	0 to -180	± 90	± 85	Continuous
Joint Accuracy, arc-min	6	6	6	6	6	6
Torque, N-m (ft-lbs)	122.4(90)	122.4(90)	63(50)	20.4(15)	20.4(15)	20.4(15)
Joint Angular Rates, rad/sec	0.2	0.2	0.4	0.2	0.2	0.2
Segment Lengths, cm (in)	Shoulder-Elbow: 127 (50) Elbow-Wrist: 112 (44) Wrist-End Effector: 36.8 (14.5)					
Segment Structure, cm (in)	Shoulder-Elbow: 10.2 (4.0) square tubing Elbow-Wrist: 9.1 (3.6) square tubing					
Arm Deflection, cm (in)	Fully Extended with 44.5 N (10 lb) Force: 0.84 (0.33)					
Natural Frequencies, hz	Loaded (300 lb module): 3.9 Unloaded: 0.97					
Actuators	Motors: D.C. Brush Type Torquers Gears: Four Branch Out of Phase Internal Output Gear System Lubrication: "HI-T" Solid Lubricant					
Brakes	Electromagnetic Friction-Disc Type					

Table V-2 Material(s) Selection Summary

Application \ Material	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

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 qualities 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.

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, unilateral rate and bilateral force reflecting control law equations were developed. Both techniques utilized a spherical base coordinate system and permitted applied manipulator forces and moments, derived from the control law equations, to be displayed at the operator's console. To facilitate variable 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.

A. 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 VI-1. In the following, a description and the function of each hardware item is presented.

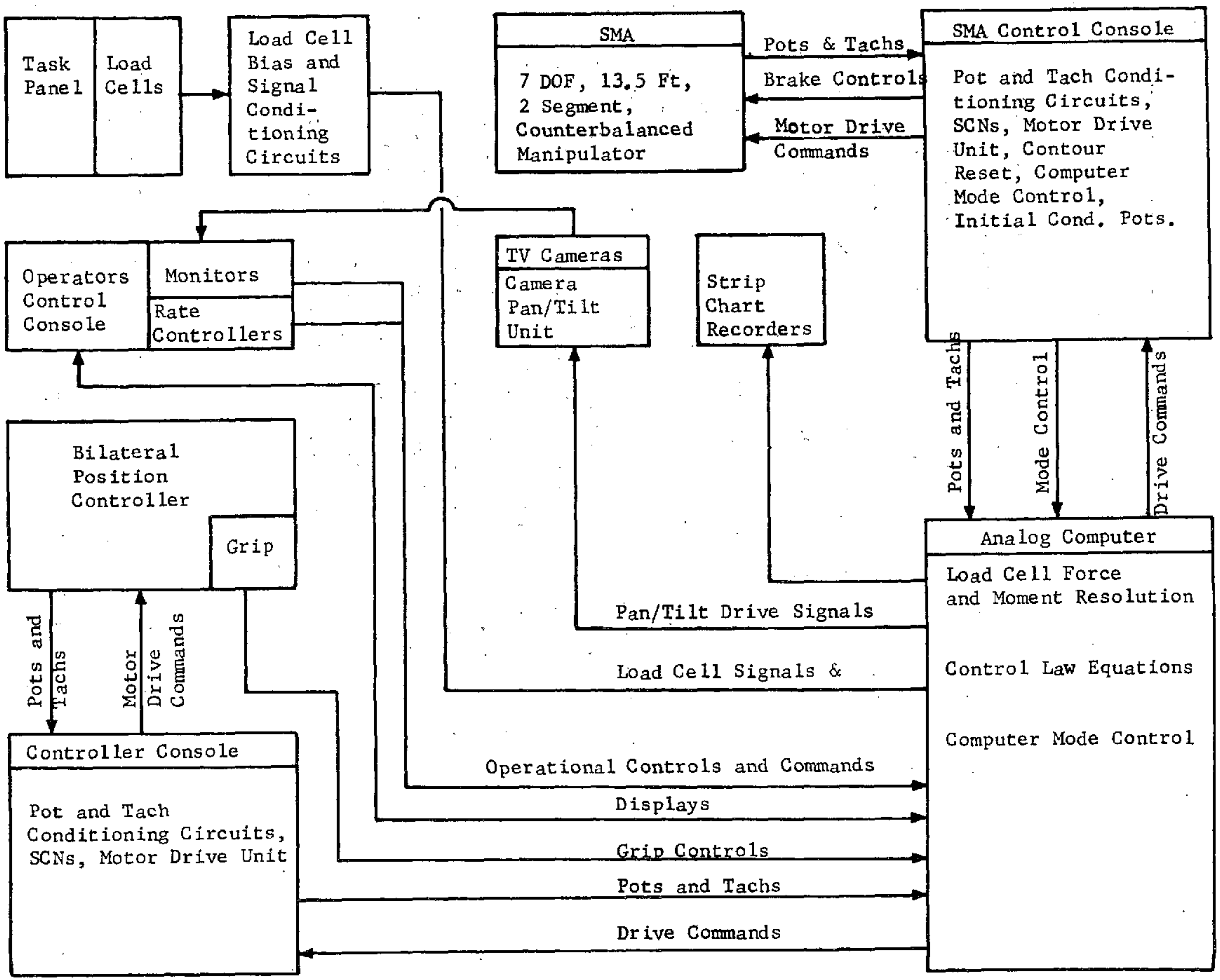


Figure VI-1 Simulation Hardware Components and Information Flow

SMA = Slave Manipulator Arm
SCN = Servo Compensating Networks

1. Slave Manipulator Arm (SMA)

The major piece of equipment utilized 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 Fig. VI-2, was used to simulate an actual manipulator arm attached to the free flyer. The manipulator wrist segment, shown in Fig. VI-3, is approximately 18 inches long.

2. SMA Control Console

The SMA control console, shown in Fig. VI-4, performs numerous functions relating to controlling the slave arm which include: signal conditioning circuits, servo compensating networks, motor drive units, contour reset, joint limits, local control and monitor functions.

3. 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 and used to close control loops around the SMA joints and the vertical-slider bilateral controller joints.

4. Operator's Control Console

The operator's control console used in this simulation is shown in Figs. VI-5 and VI-6. Fig. VI-5 shows mainly the display parameters used by the manipulator operator determining his input commands. The displays and controls include manipulator joint angle, force and torque meters; mono and stereoscopic TV monitors; translational and rotational rate controllers; and a TV camera pan/tilt pencil type controller. Fig. VI-6 shows additional control functions available to the operator such as position control motion ratio, rate control ratio, force and torque ratios, and TV controls.

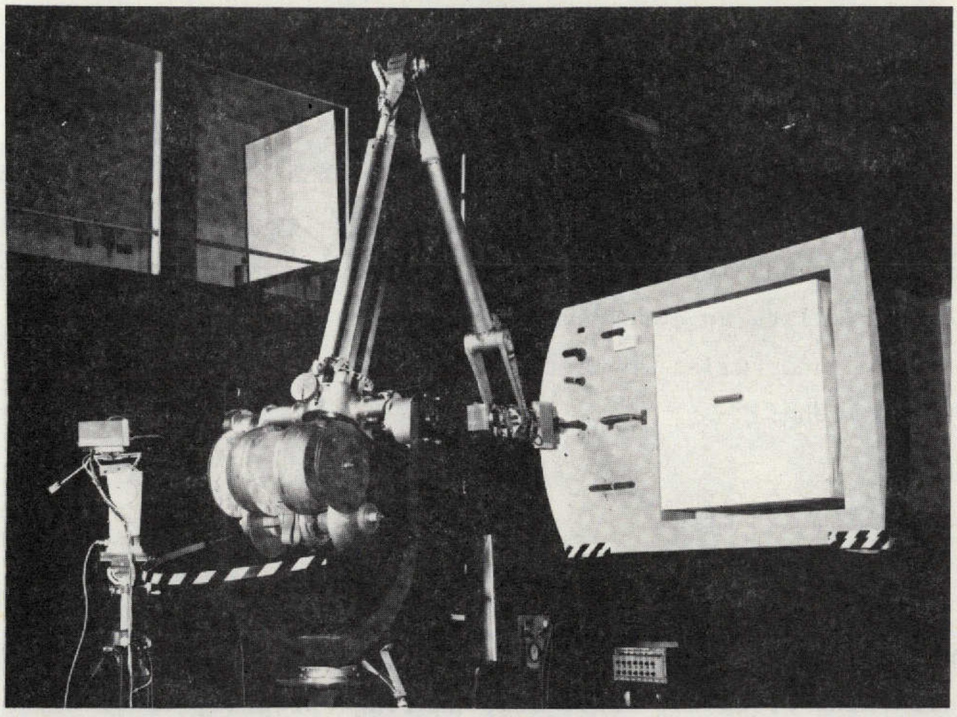


Figure VI-2 Slave Manipulator Arm (SMA)

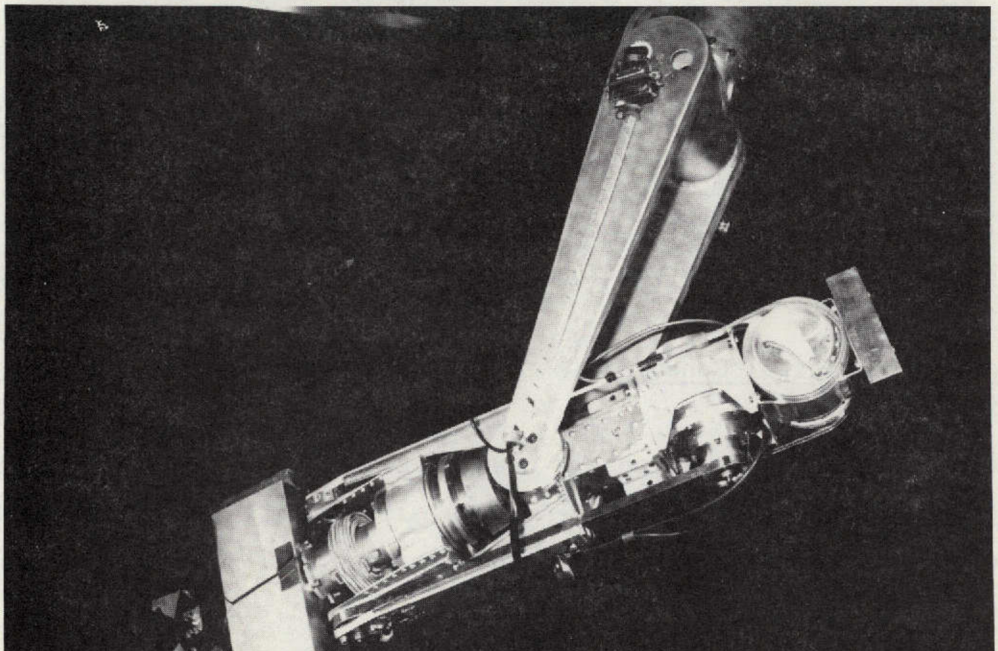


Figure VI-3 SMA Wrist Assembly

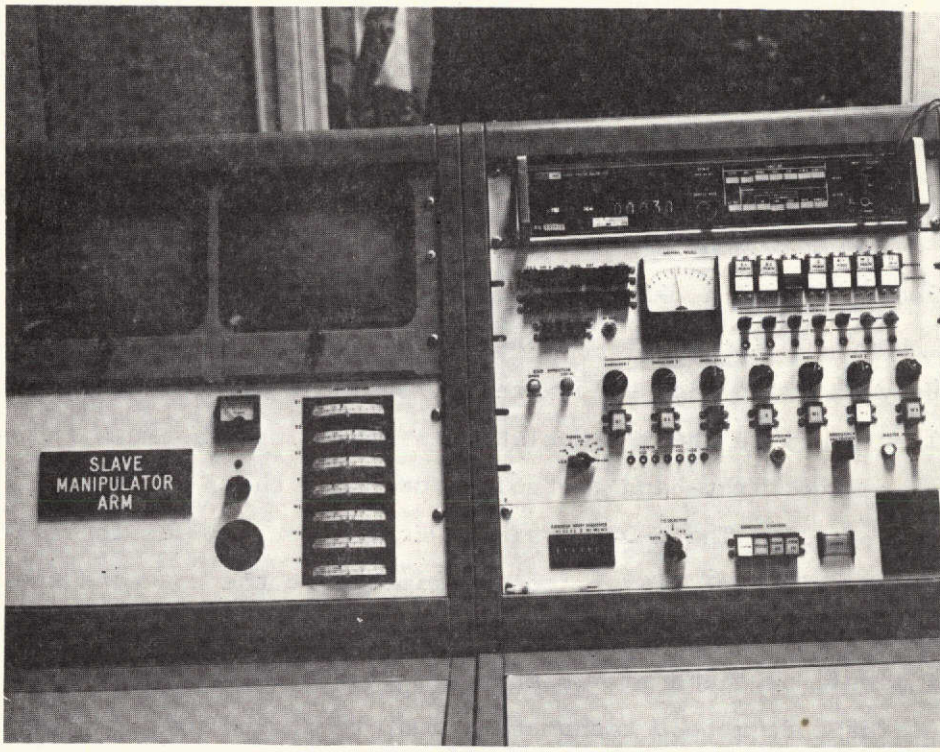


Figure VI-4 SMA Control Console

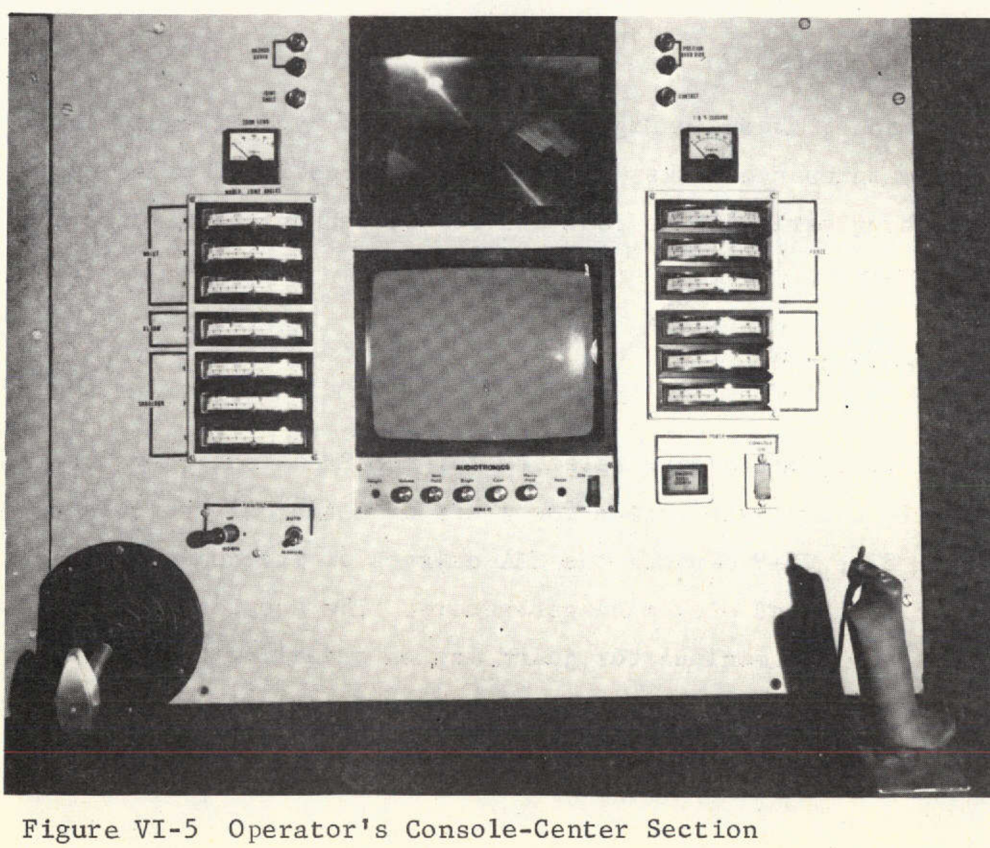


Figure VI-5 Operator's Console-Center Section

5. Controllers

Two types of input hand controllers were utilized in these simulations: a) two 3-DOF Apollo type rate hand controllers used for the rate control system, and b) a 6-DOF vertical sliding type bilateral hand controller used for the position control mode. The two rate controllers, previously shown in Fig. VI-5, are proportional type. 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. The 6-DOF position controller and its control console is shown in Fig. VI-7. The two gimbals at the base and the vertical slide provided translational control which the three gimbals about the control handle provided manipulator wrist attitude control. Each gimbal contains a dc motor, tachometer, gear train and potentiometer to provide force-feedback to the operator.

6. Task Panel

The task panel, shown in Fig. IV-8, simulated typical manipulator service and maintenance tasks. The panel contains fixed bars, recepticles for inserting various size rods and boxes, and friction force and torque devices.

B. CONTROL EQUATIONS

Spherical coordinates were selected for the SMA since they are truly a "natural" coordinate system for a six or seven DOF articulated manipulator. Fig. VI-9 depicts the SMA degrees of freedom and defines the range, azimuth, and elevation parameters. The equations relate these parameters to the manipulator joint angles revealing the simplicity of using the spherical approach. Rotational control of the manipulator wrist is accomplished on a one-to-one basis.

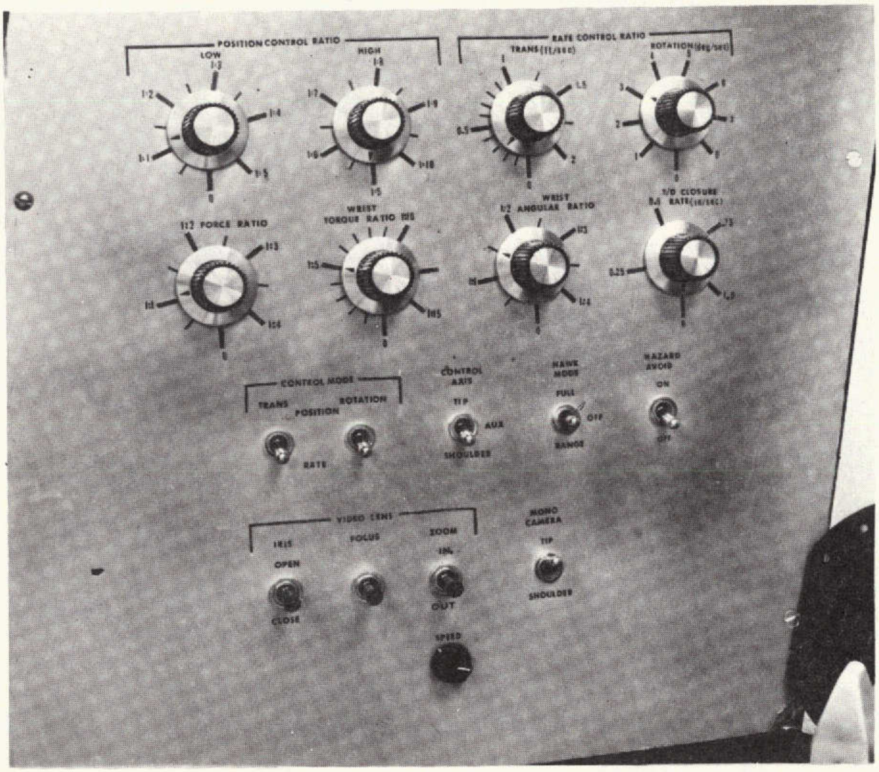


Figure VI-6 Operator's Console-Left Section

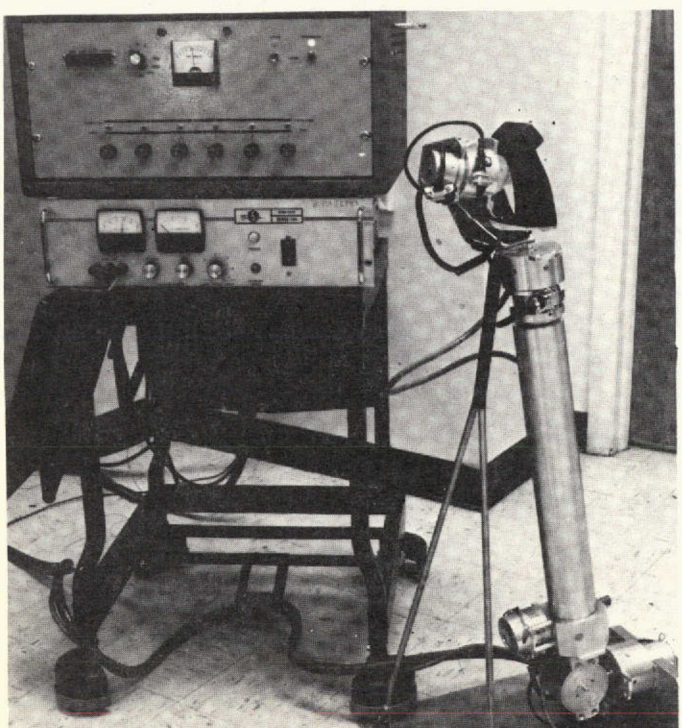


Figure VI-7 Nongeometric Bilateral Controller (Vertical Slider)

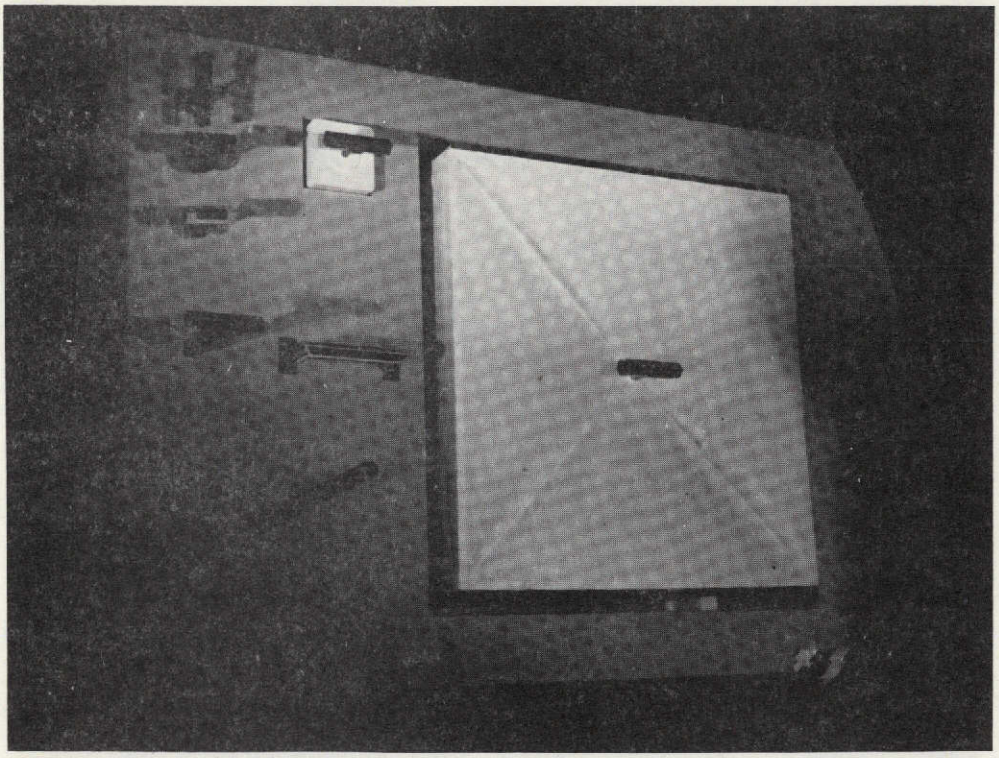
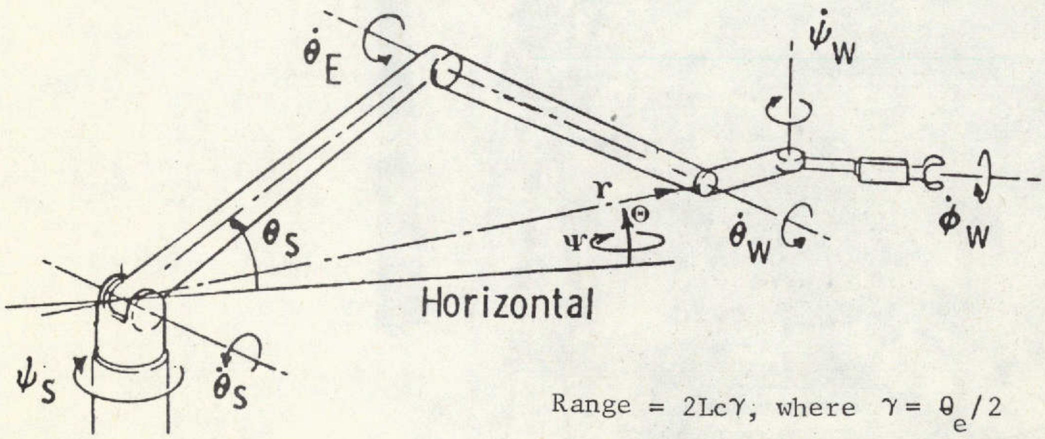


Figure VI-8 Task Panel



Range = $2Lc\gamma$, where $\gamma = \theta_e/2$

Elevation = $\theta_s + \gamma$

Azimuth = $\emptyset_s$

Figure VI-9 Control Laws

C. SIMULATION TASKS

Each operator was required to accomplish specific tasks which included angular alignment, push/pull a linear translational friction rod, rotate a lever, and insert/retract a pin in a "close tolerance" recepticle.

D. RESULTS

From the information gained in the SMA simulation, range/azimuth/elevation/rotation rate control technique was 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, trade studies, and the results of the man-in-the-loop simulations.

A. MANIPULATOR SYSTEM

The preliminary design drawings for the FFTS manipulator system are shown in Figs. VII-1 through VII-7.

The general characteristics of the configuration are:

OVERALL LENGTH:	276 cm (108.5 in)
TOTAL WEIGHT:	38 kg (83.9 lbs)

The manipulator contains actuators at each of 6 joints plus an end effector drive mechanism. Each actuator incorporates a motor, tachometer, gear train, bearings, potentiometer and brake.

1. Gear Design

The gear train within each actuator is a four branch, out of phase internal output system. 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. The following gear ratios are incorporated into the preliminary design:

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

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

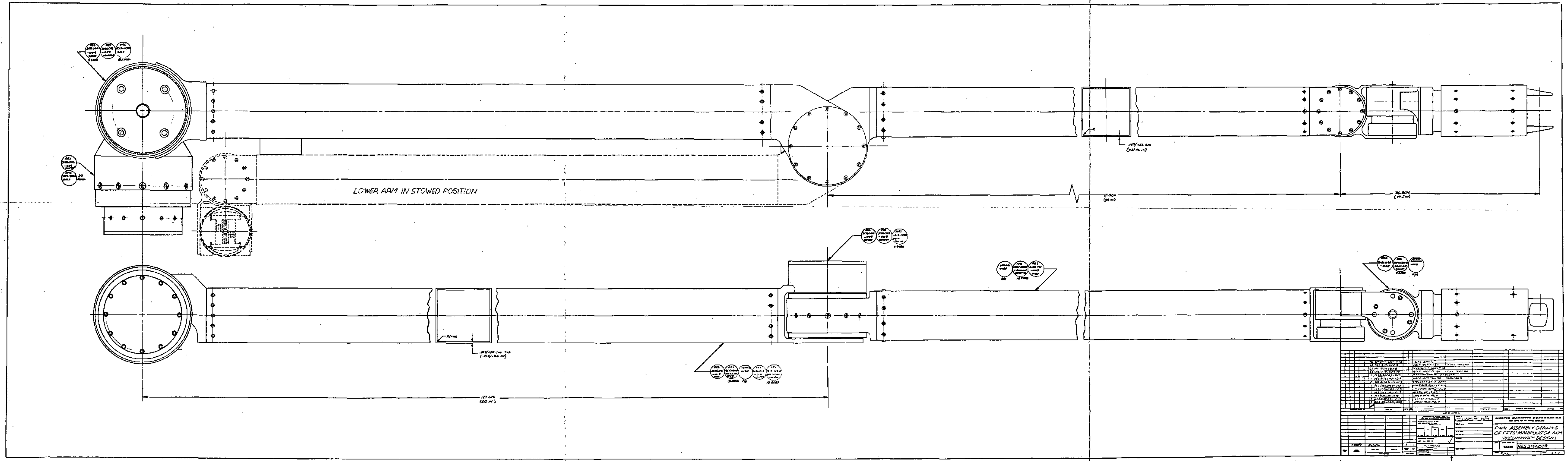


Figure VII-1 Final Assembly Drawing of FFTS Manipulator Arm

FOLDOUT FRAME

FOLDOUT FRAME 2

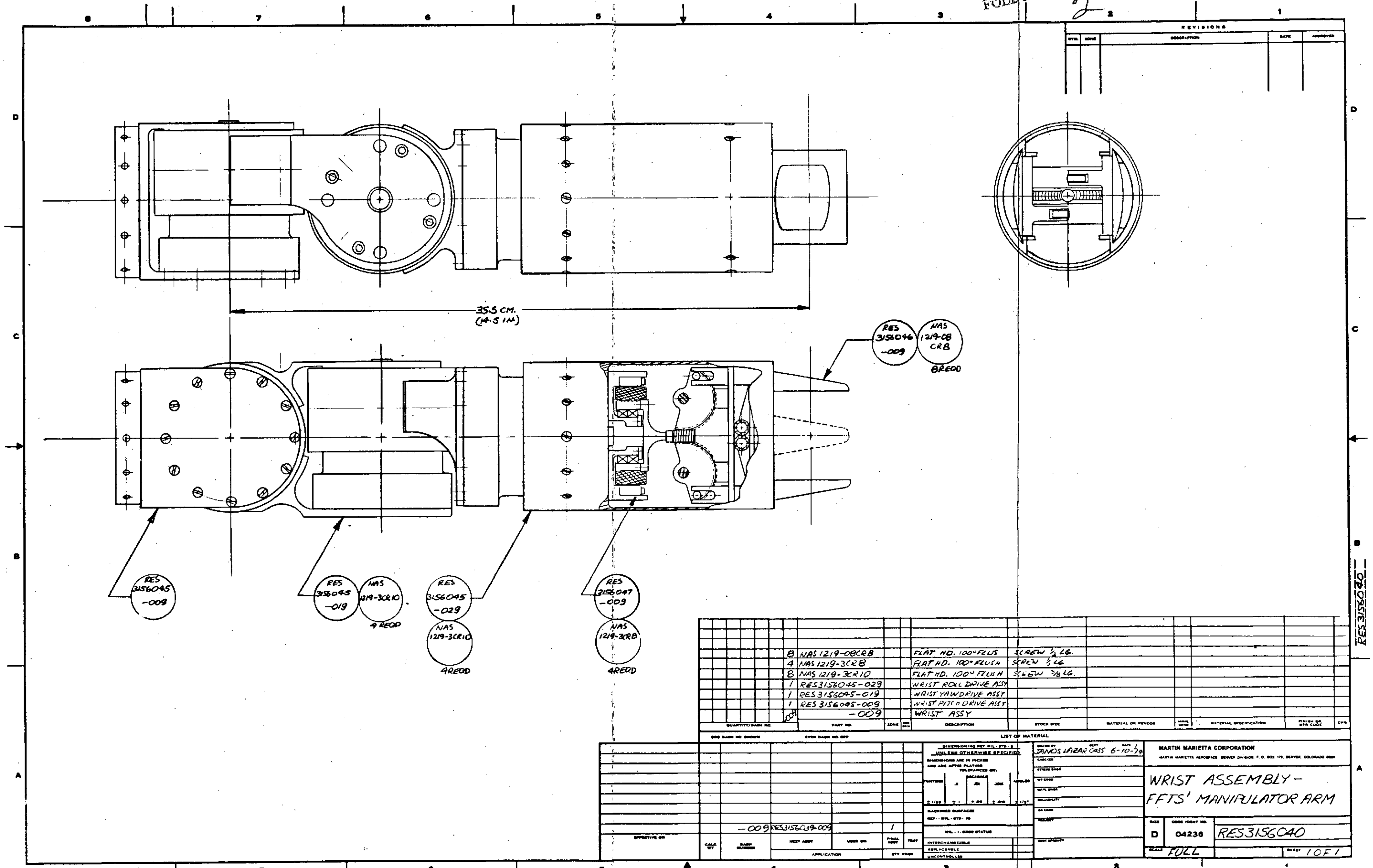


Figure VII-2 Wrist Assembly

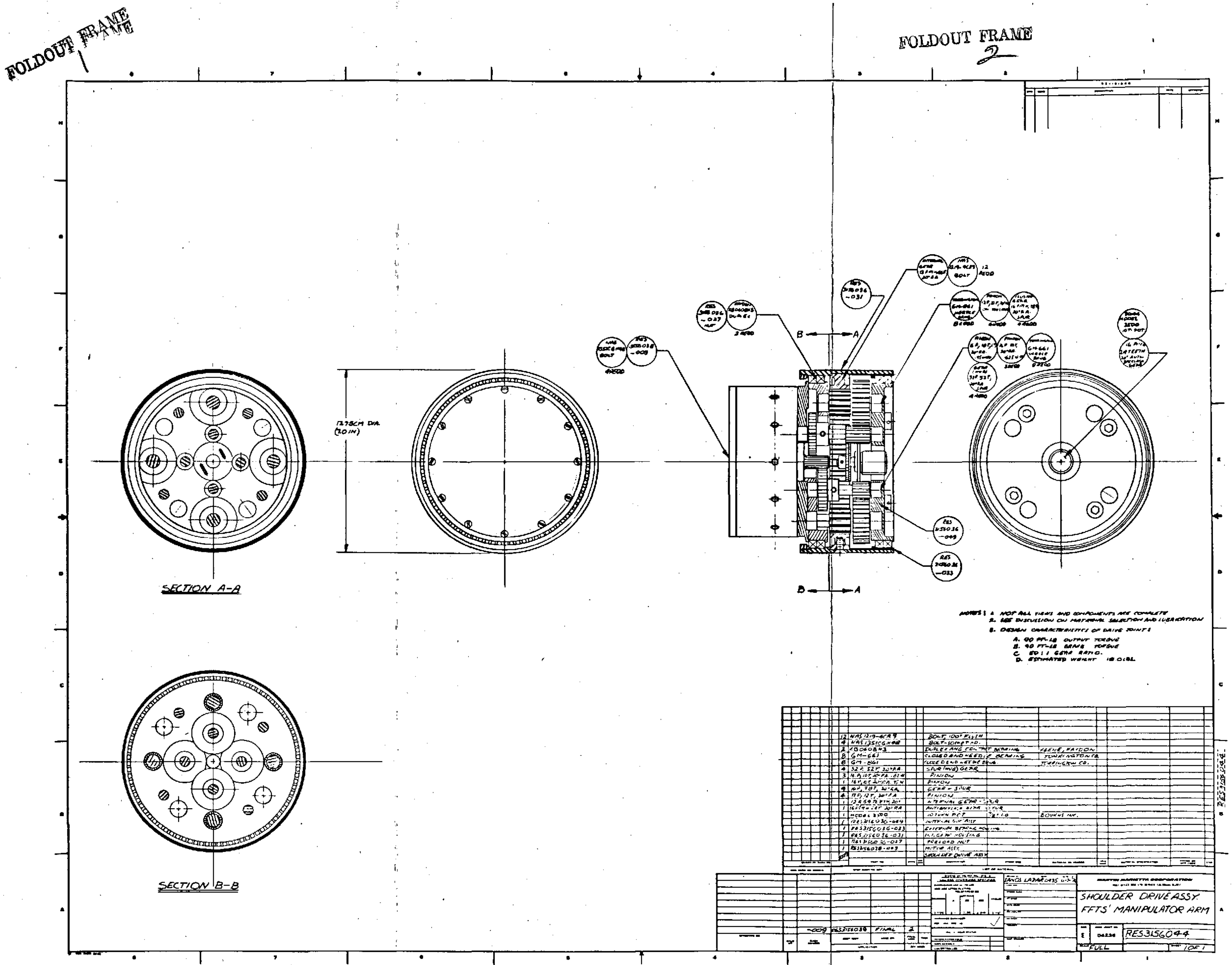
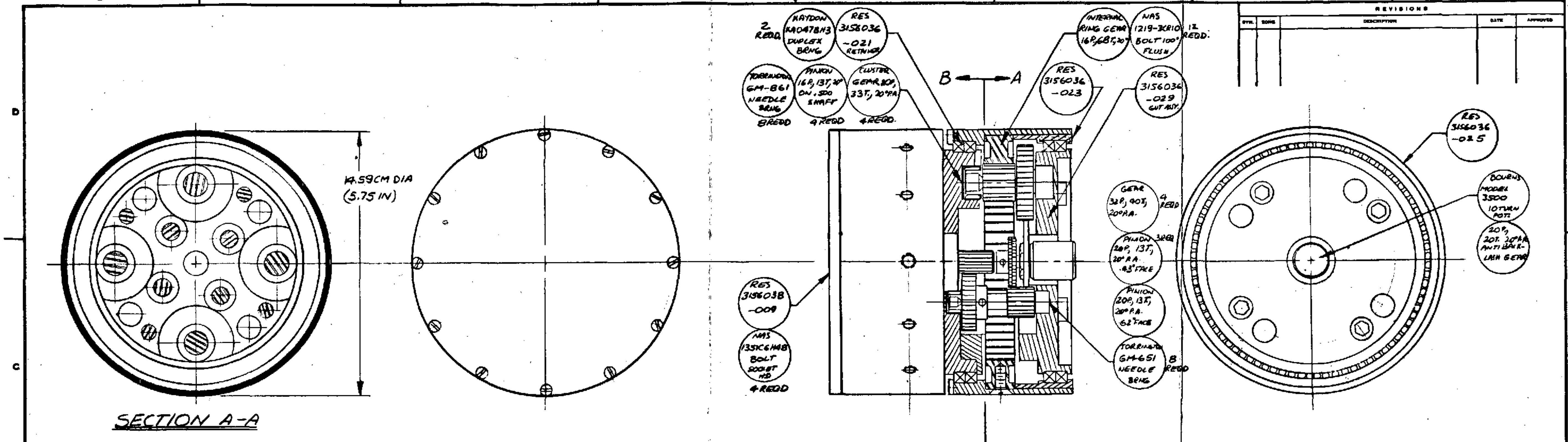
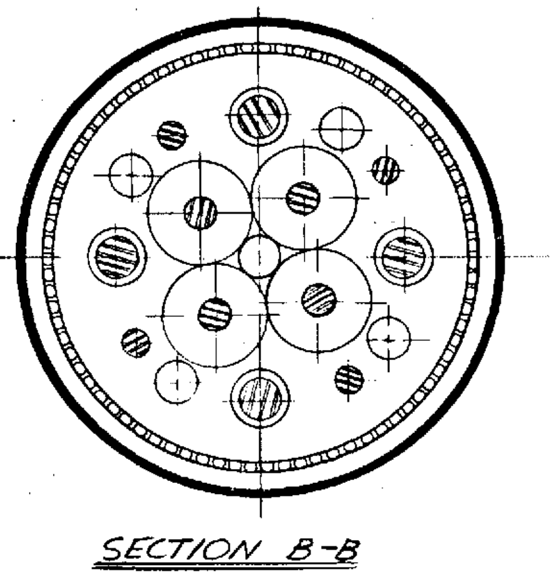


Figure VII-3 Shoulder Drive Assembly

FOLDOUT FRAME 1

FOLDOUT FRAME 2





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. 50 FT-LB BRAKING TORQUE
   C. 332:1 GEAR RATIO
   D. ESTIMATED WEIGHT 14 LBS.

QUANTITY/DASH NO.	PART NO.	ZONE	DESCRIPTION	STOCK SIZE	MATERIAL OR VENDOR
12	NAS 1219-3CR10		BOLT 100° FLUSH		
4	NAS 1351C6H48		BOLT SOCKET HD.		
2	KA047BH3		DUPLEX BALL BEARING		KEENE CORP-KAYDON
8	GM-861		NEEDLE BEARING		TORRINGTON CO.
8	GM-651		NEEDLE BEARING		TORRINGTON CO.
4	32 PITCH, 40T, 20° P.A.		GEAR - HUB		
3	20 PITCH, 13T, 20° P.A.		PINION	.43 FACE	
1	20 PITCH, 13T, 20° P.A		PINION	.62" FACE	
4	20 PITCH, 33T, 20° P.A.		GEAR		
4	16 PITCH, 13T, 20° P.A.		PINION, ON .5000 SHAFT		
1	16 PITCH, 52T, 20° P.A.		INTERNAL RING GEAR	5/8" FACE	
1	20 PITCH, 20 TEETH,		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	-009		ELBOW DRIVE ASSY		

LIST OF MATERIAL

APPLICATION: -009 RES3156039-009 1

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND ARE AFTER PLATING

DRAWN BY: JANOS LAZAR 0935 6-8-79

MARTIN MARIETTA CORPORATION
POST OFFICE BOX 179, DENVER, COLORADO 80201

ELBOW DRIVE ASSEMBLY
FFTS' MANIPULATOR ARM

SIZE D CODE IDENT NO. 04236 RES3156042

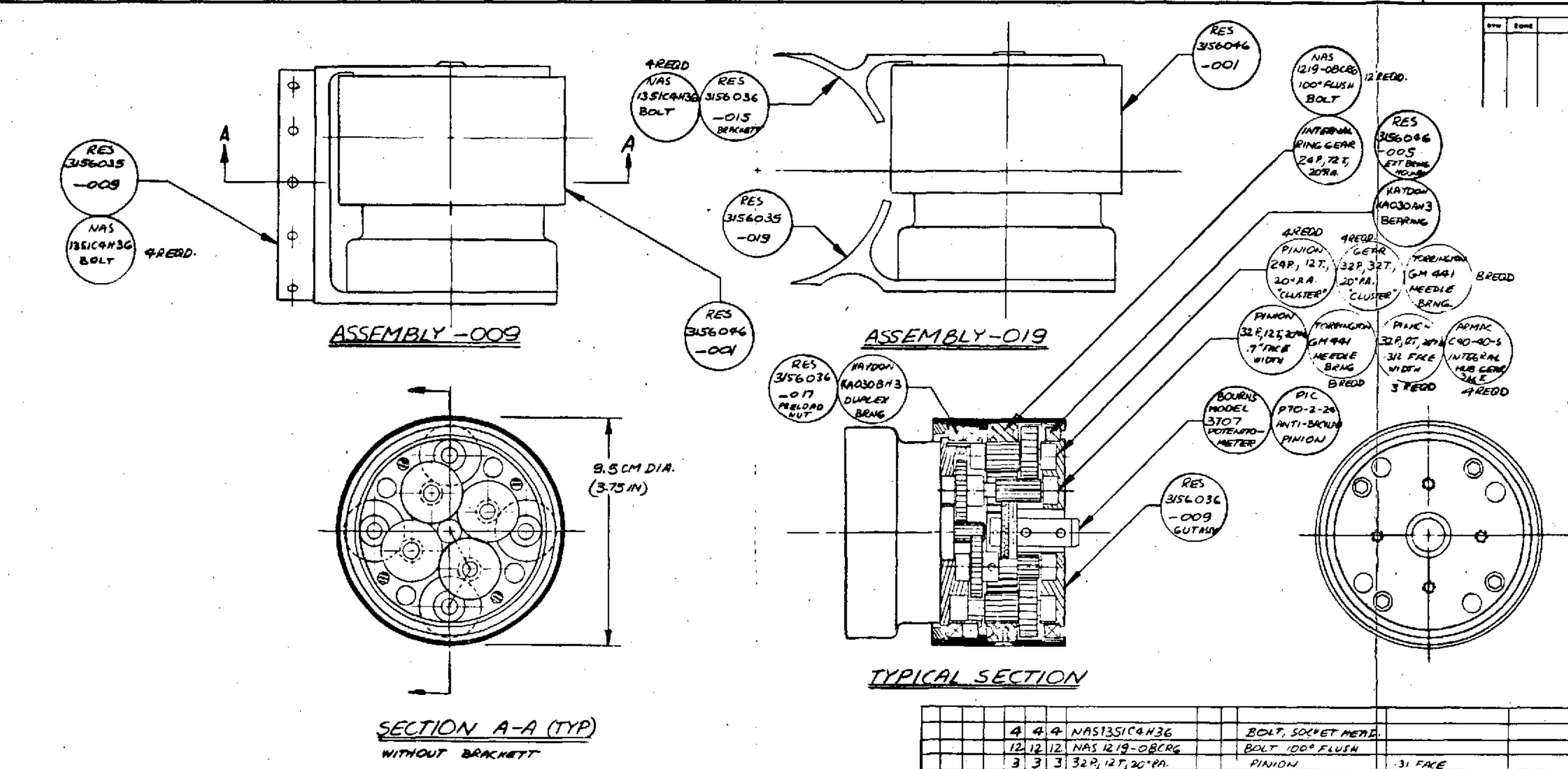
SCALE FULL SHEET 1 OF 1

RES3156042

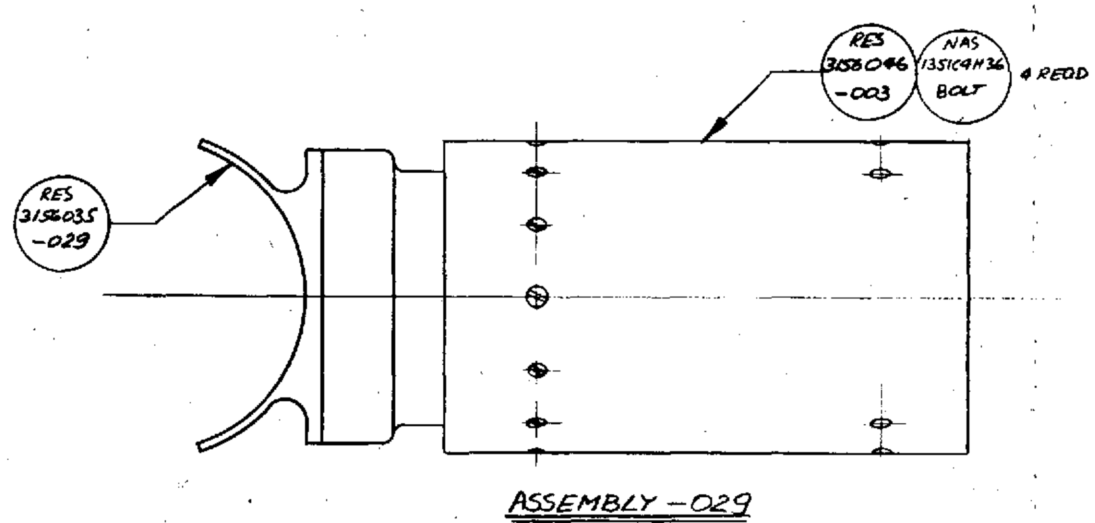
Figure VII-4 Elbow Drive, Assembly

FOLDOUT FRAME 1

FOLDOUT FRAME 2



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



WEIGHT 4 LBS ± 5%
RATIO 42.6
FORWARD TORQUE: 15 FT-LB MAX.
REVERSE TORQUE: 15 FT-LB MIN.

-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	.70 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, 3/16 FACE	INTEGRAL HUB GEAR		FRANKIE GEAR WORKS	INC.	
16	16	16	GM441	CLOSED END NEEDLE BEARING		TORRINGTON CO		
1	1	1	KA030BH3	BEARING-DUPLEX-KAYDON		KEENE CORP		
1	1	1	KA030AH3	BEARING-KAYDON		KEENE CORP		
	1	1	P70-2-24	ANTI BACKLASH PINION		PICK 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 SHELL				
	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.				
			-009	WRIST DRIVE ASSY.				

QUANTITY / DASH NO — ODD DASH NO. SHOWN — EVEN DASH NO. OPP. — LIST OF MATERIAL

-029	RES3156046-029	
-019	RES3156046-019	
-009	RES3156046-009	
DASH NUMBER	NEXT ASSY	USED ON

DIMENSIONING PER MIL-STD-8. UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND ARE AFTER PLATING

DRAWN BY JANOS LAZAR 0435 6-2-74

MARTIN COMPANY
DIVISION OF MARTIN MARIETTA CORPORATION

WRIST DRIVE ASSEMBLY– FFTS' MANIPULATOR ARM

CODE IDENT. NO. 38597 — SIZE D — RES 3156045

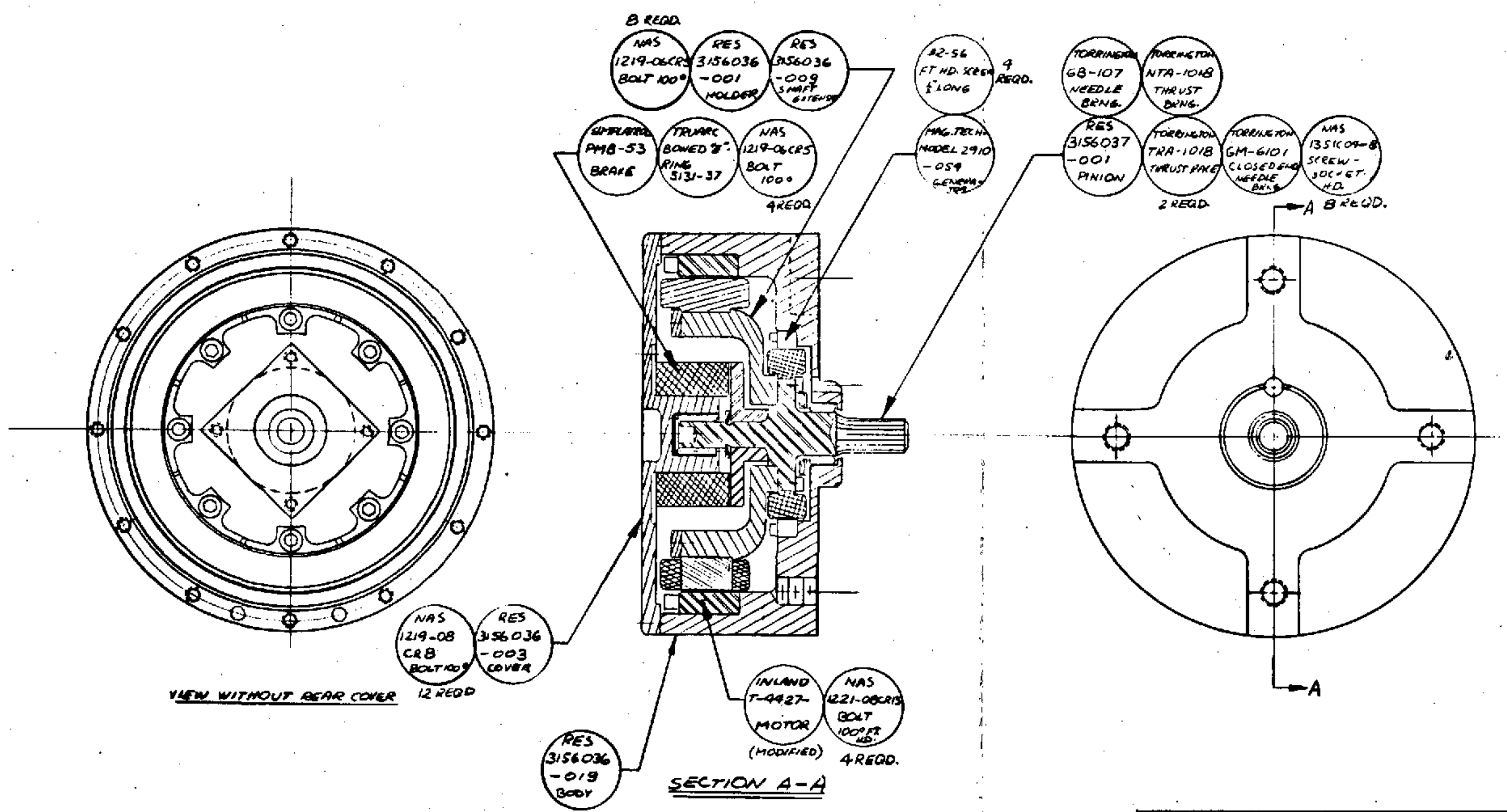
SCALE FULL — SHEET 1 OF 1

RES3156045

Figure VII-5 Wrist Drive Assembly

FOLDOUT FRAME

FOLDOUT FRAME 2



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

REVISIONS

SYM	ZONE	DESCRIPTION	DATE	APPROVED

LIST OF MATERIAL

QUANTITY/DASH NO.	PART NO.	ZONE	DESCRIPTION	STOCK SIZE	MATERIAL OR VENDOR	MATERIAL SPECIFICATION	FINISH OR MFR CODE
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	5131-31		BOWED "E" RING	3/8" SHAFT	TRUARC-WALDES		
8	NAS 1351C04-8		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.				

ODD DASH NO SHOWN — EVEN DASH NO. OPP

DASH NUMBER	NEXT ASSY	USED ON	FINAL ASSY
-009	RES 3156044-009		1
-009	RES 3156042-009		1

APPLICATION

DIMENSIONING REF MIL-STD-8
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES AND ARE AFTER PLATING
TOLERANCES ON: FRACTIONS ±1/64; DECIMALS .X ±.1, .XX ±.03, .XXX ±.010; ANGLES ±1/2°
MACHINED SURFACES REF: MIL-STD-10
MIL-I-8500 STATUS: INTERCHANGEABLE / REPLACEABLE / UNCONTROLLED

DRAWN BY: JANOS LAZAR DEPT: 0435 DATE: 6-6-74

MARTIN MARIETTA CORPORATION
POST OFFICE BOX 179 DENVER, COLORADO 80201

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

SIZE: D CODE IDENT NO.: 04236 RES 3156038

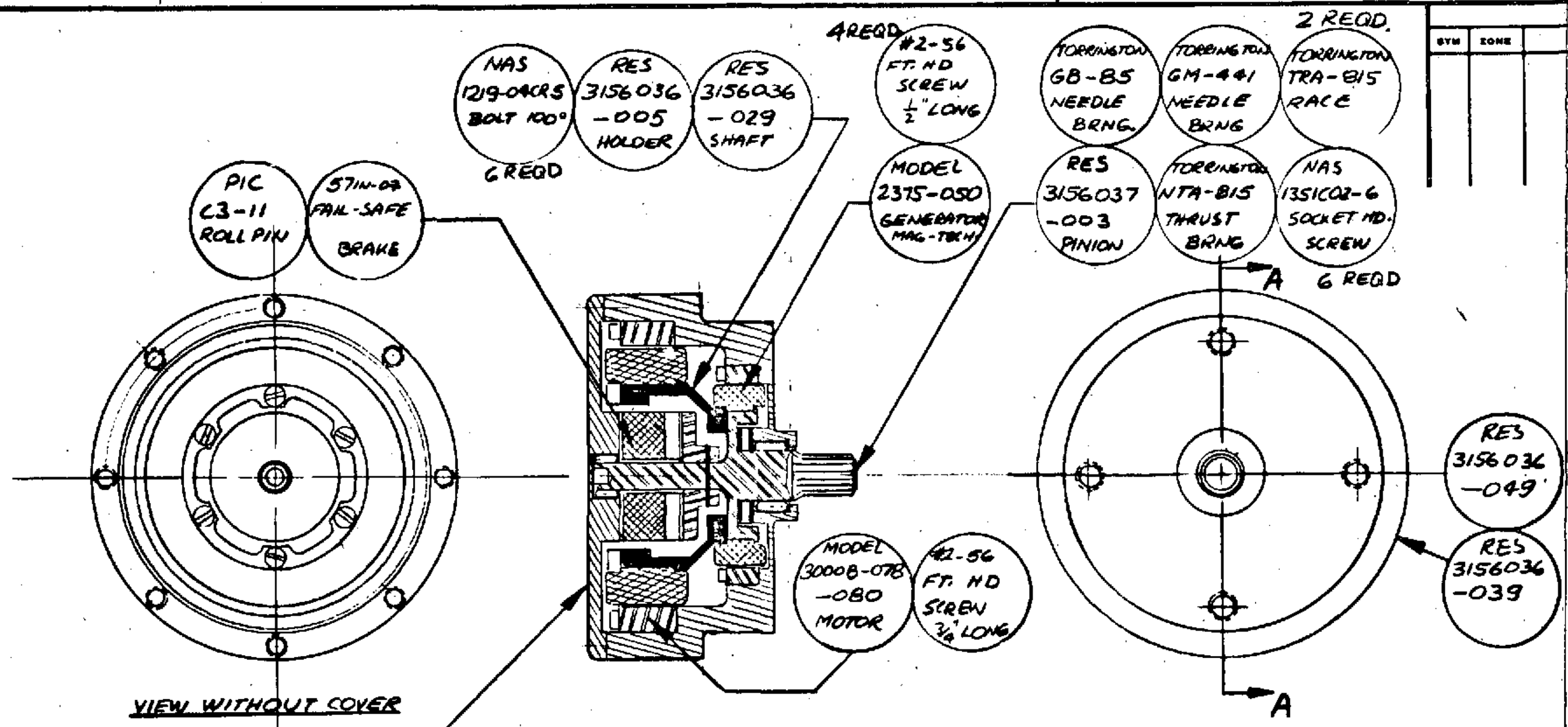
SCALE: FULL SHEET 1 OF 1

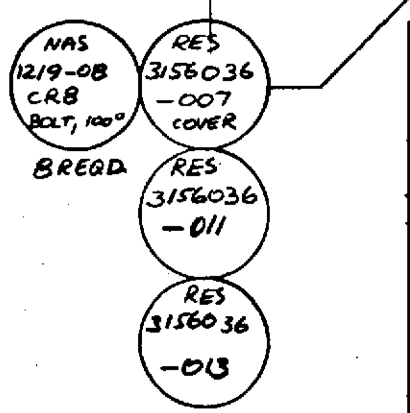
RES 3156038

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

FOLDOUT FRAME

FOLDOUT FRAME 2





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

REVISIONS				
SYM	ZONE	DESCRIPTION	DATE	APPROVED

-029	-019	-009	PART NO.	ZONE	SEE SYM	DESCRIPTION	STOCK SIZE	MATERIAL OR VENDOR	ISSUE COND	MATERIAL SPECIFICATION	FINISH OR MFR CODE	CHG
1			RES3156036-013			MOTOR COVER (ROLL)						
	1		RES3156036-011			MOTORCOVER (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		PIC. DES. CORP.				
2	2	2	TRA-815			RACE		TORRINGTON				
1	1	1	NTA-815			NEEDLE THRUST		↕				
1	1	1	GM-441			NEEDLE BRNG. CLOSED END						
1	1	1	GB-85			NEEDLE BEARING		TORRINGTON				
6	6	6	NAS1351C02-6			SOCKET HD. SCREW						
6	6	6	NAS1219-04CR5			BOLT, 100° FLUSH						
8	8	8	NAS1219-08CR8			BOLT, 100° FLUSH						
1	1	1	MBF12-28-C-2-B			BRAKE		VERNITRON CORP.				
1	1	1	MODEL 2375-050			GENERATOR		MAGNETIC TECHNOLOGY				
1	1	1	MODEL 3000B-078-080			MOTOR	28 VDC.	MAGNETIC TECHNOLOGY				
1	1	1	RES3156037-003			PINION-SPECIAL	40 PITCH, 15 TEETH,	20° P.A., 9310 STEEL OR		EQUIV. Q-12, STRAIGHT TEETH.		
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						
QUANTITY/DASH NO.												

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

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

EFFECTIVE ON | CALC WT | DASH NUMBER | 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 / GP 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 | RES3156035
SCALE FULL | SHEET 1 OF 1

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

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. The contact stress levels of the gear trains are designed within the 140,000 psi "safe" operational region of this lubricant.

2. Bearing Selection

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-hardened to .0004" thickness only and acts as a cushion for the needles such that the contact area per needle is increased and the contact stress is low.

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.

3. Motor Selection

The motors are dc brush type torquers and were selected based upon "state-of-the-art" considerations and providing commonality of motor types within the manipulator design. Two motor types are used: one for the shoulder and elbow joints and one for the three wrist gimbals. The characteristics of the motors are summarized in Table VII-1.

Table VII-1 Motor Characteristics

	Output Torque (ft-lbs)	Input Torque (in-oz)	Gear Ratio	Weight (oz)	Speed at Maximum Torque (rad/sec)	No Load Speed (rad/sec)	Maximum Oper. Power (watts)	Maximum Stall Power (watts)
Shoulder (2) (T-4427)	90	384	50	48	0-0.2	0.5	70.3	43.5
Elbow (1) T-4427	50	384	30	48	0-0.4	0.9	67.5	37.4
Wrist (3) (30008-078)	15	120	42.6	10.2	0-0.2	1.4	32.4	28.1

B. CONTROL SYSTEM

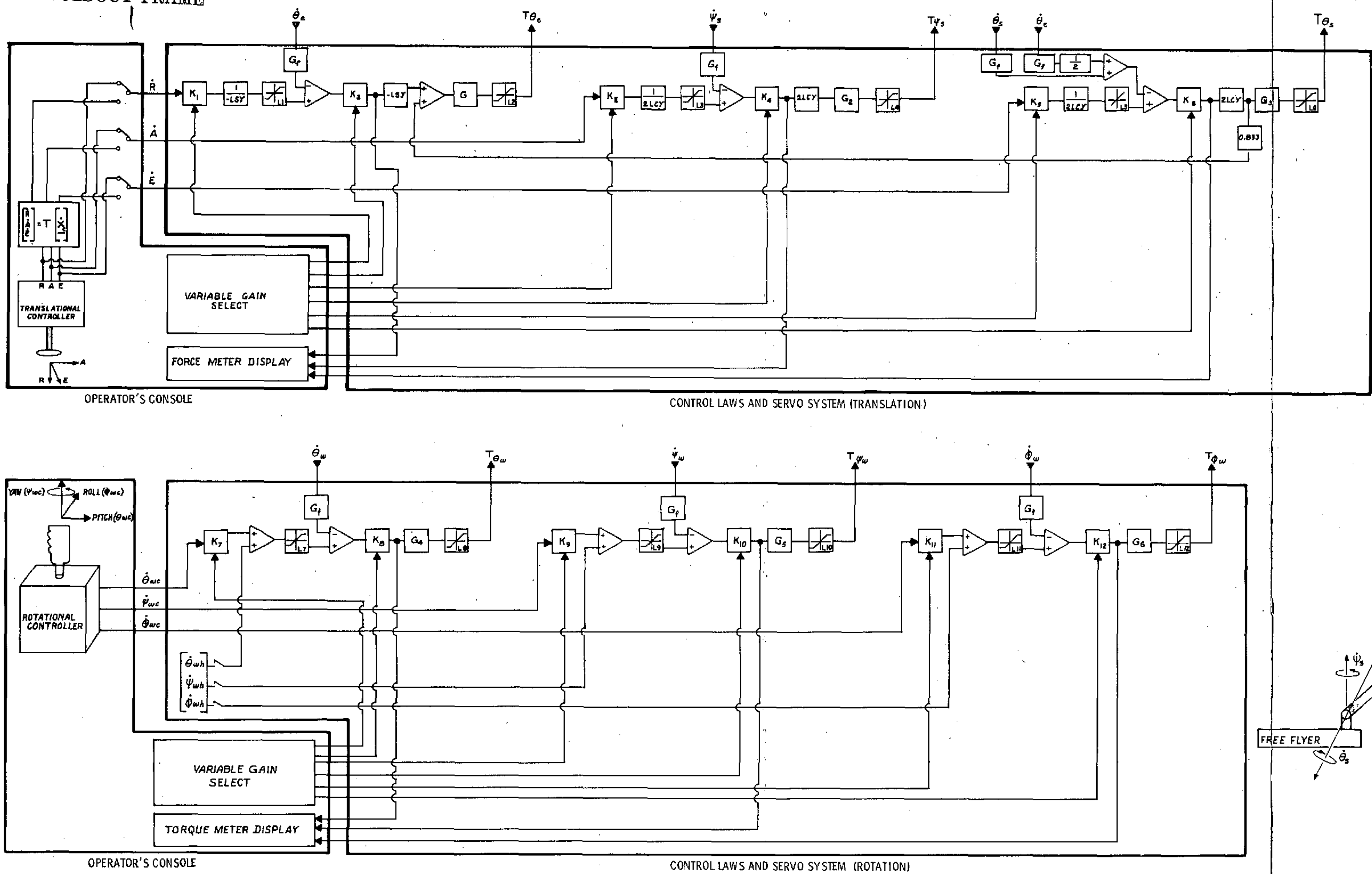
The RAE/Rotation control mode was selected for the preliminary design. Fig. VII-8 depicts the complete RAE/Rotation control scheme. Signals received by the control system from the input rate controllers and gimbal sensors, as well as computed information transmitted to the operator's console and joint actuators are detailed.

The manipulator control 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 translational rate controller. Rotational control of the wrist assembly is accomplished by associating each rotational rate controller degree of freedom on a one-to-one basis with its counterpart gimbal on the manipulator wrist.

C. DATA MANAGEMENT

A basic diagram relating a manipulator of typical component complement to a remotely located man/machine interface is shown in Fig. VII-9. The elements located on the FFTS include manipulator actuator and sensors, telemetry signal conditioning, command reception and conditioning for the manipulator servo actuators.

FOLDOUT FRAME



FOLDOUT FRAME

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. $\gamma = 1/2\ \theta_c$
7. L = Lower arm segment length
8. $\dot{\theta}_{wc}$, $\dot{\psi}_{wc}$, $\dot{\phi}_{wc}$ = commanded wrist attitude rates
9. $\dot{\theta}_{wh} = -\dot{\theta}_e - \dot{\theta}_s - T\psi_w S\theta_1 \dot{\psi}_s$
   $\dot{\psi}_{wh} = -C\theta_1 \dot{\psi}_s$
   $\dot{\phi}_{wh} = \frac{S\theta_1 \dot{\psi}_s}{C\psi_w}$, 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

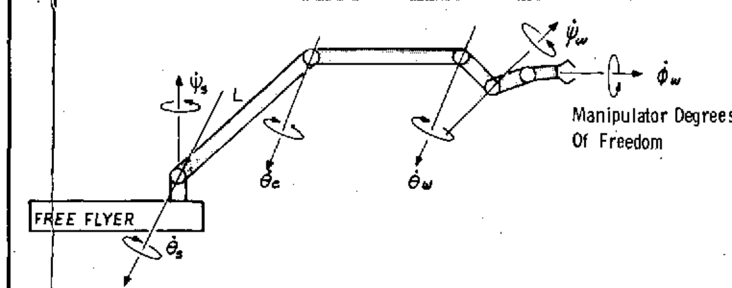


Figure VII-8 RAE/Rotation Control System

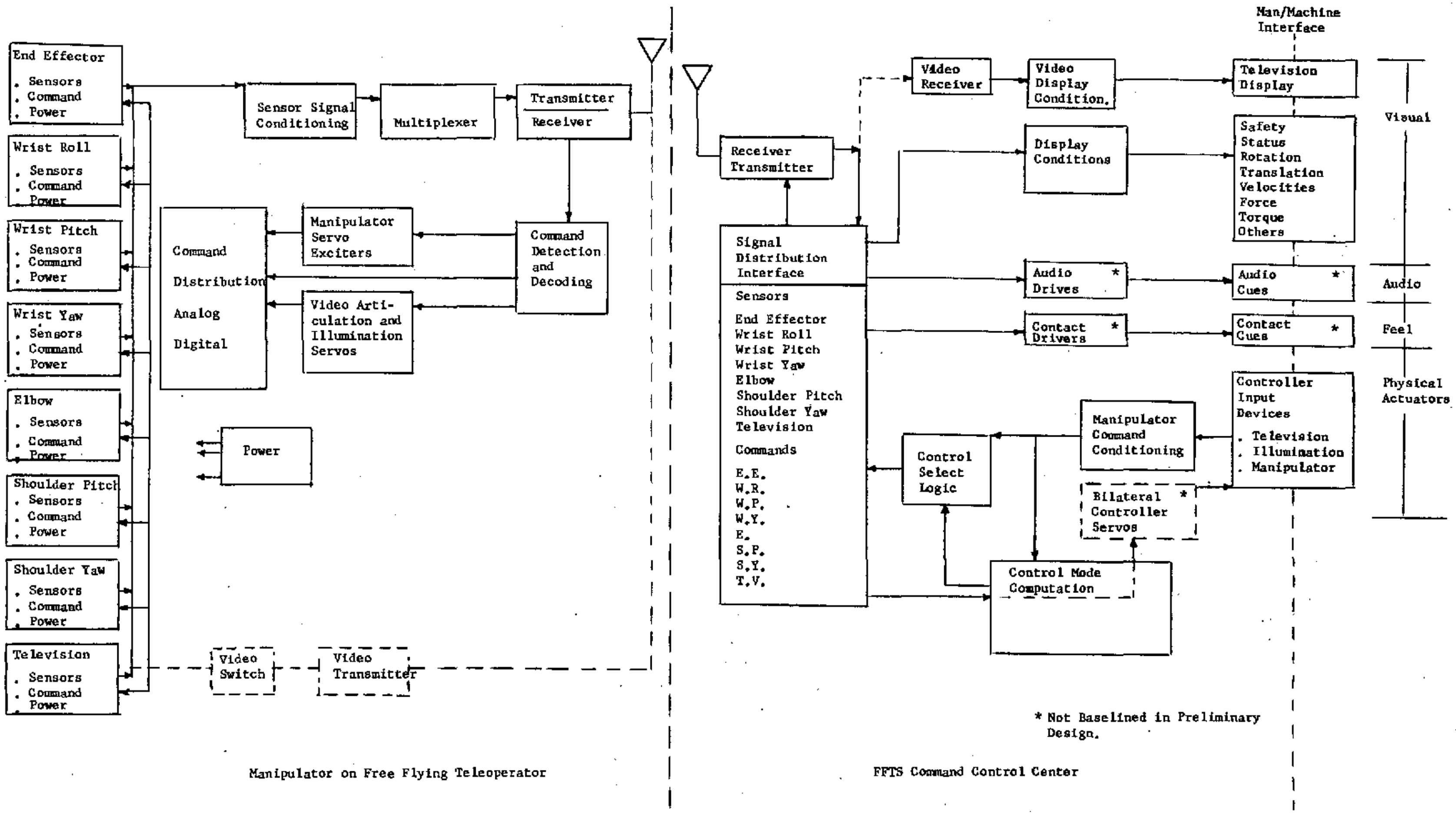


Figure VII-9 Major Manipulator Data Sources and Interrelationships

The man/machine interface consists of television displays, auxiliary visual displays, and the physical input devices for manipulator and television control. Manipulator input devices are conditioned from controller coördinates to manipulator actuator coordinates by a control mode computation unit. 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.

An analysis of signal sampling rate requirements established the system bandwidth.

Briefly, it was established 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.

D. CONTROL AND DISPLAY STATION

The FFTS control and display station (CDS) may be located in the Shuttle, a sortie laboratory, or on the ground and provides the man/machine interface necessary for the remote manned supervisory control of the FFTS.

A preliminary design layout of the CDS is shown in Fig. VII-10. The layout integrates the manipulator control and display elements into a total integrated FFTS CDS. The initial starting point for the CDS was based upon the material contained in Ref. 12 and updated to incorporate the requirements resulting from the man-in-the-loop manipulator simulations.

As seen in Fig. VII-10, the controls and displays of the primary FFTS subsystems were incorporated which include visual, propulsion, guidance/navigation, communication, docking, and manipulator. These have been positioned about the two video displays. The upper display is a stereo-Fresnel and the lower is a monoscopic display.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

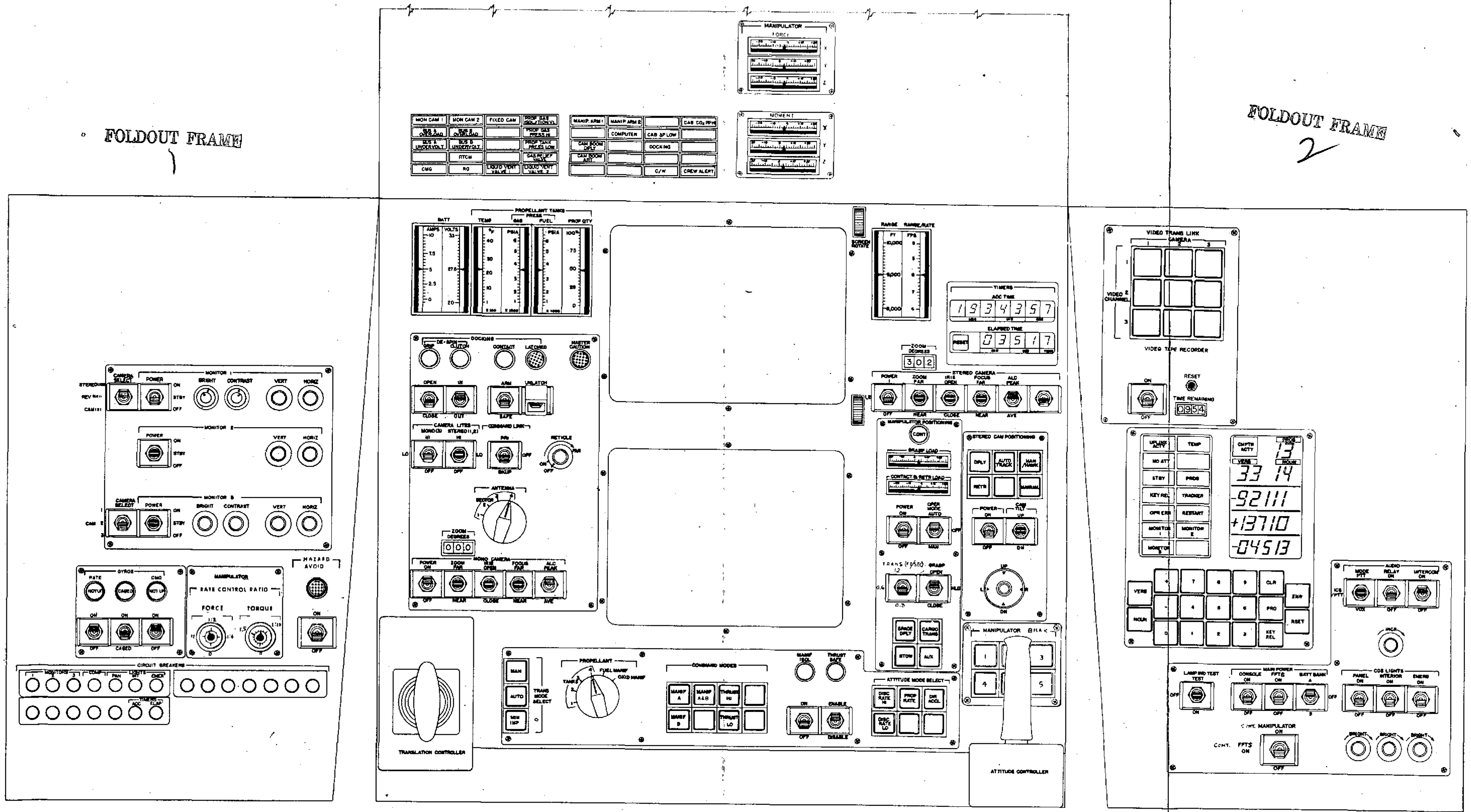


Figure VII-10 FFTS Integrated Control and Display Station

The control and displays required specifically for the manipulator subsystem are summarized in Table VII- 2.

Table VII- 2 Manipulator Control and Display Type Hardware and Selection Rationale

Control or Display Requirement	Type Selected	Rationale
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.

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. <u>Detailed Actuator Trade Studies</u>

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. <u>Incorporation of Brakes within the Control System</u>

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.

IX. REFERENCES

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3. Rechnitzer, A. B., Sutter, W. "Naval Applications of Remote Manipulation", Proceedings of the First National Conference on Remotely Manned Systems, California Institute of Technology, September, 1972.
4. "Preliminary Requirements Analysis", Task 2 Final Report, Contract NAS8-30266, Configuration and Design Study of Manipulator Systems Applicable to the Free Flying Teleoperator, MCR-73-312, Martin Marietta Corporation, Denver, Colorado, December, 1973.
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