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Final Report April 1977

Proto-Flight Manipulator Arm (P-FMA)

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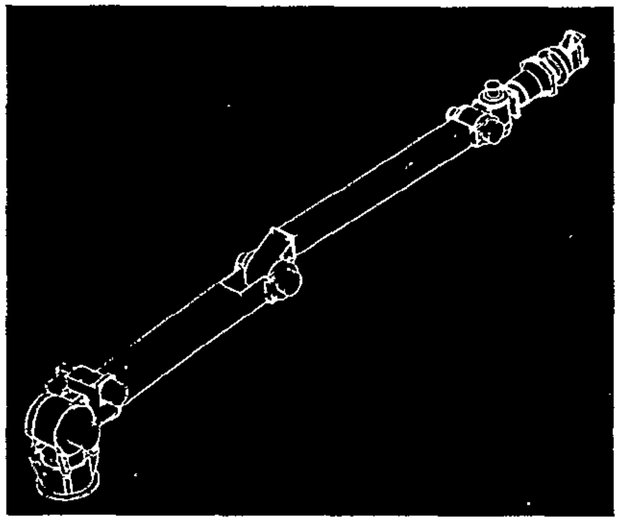

MARTIN MARIETTA

FINAL REPORT

OF THE

PROTO-FLIGHT MANIPULATOR ARM (P-FMA)

Contract NAS8-31487

Document Number MCR-77-201

April 1977

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ABSTRACT

This document is prepared and submitted in accordance with the requirements of Exhibit A, paragraph IV.2, of Contract NAS8-31487. It provides a summary of the technical development of the *Proto-Flight Manipulator Arm (P-FMA)* which is a seven-degree-of-freedom general-purpose arm capable of being remotely operated in an earth orbital environment. Conclusions and recommendations are offered for NASA's consideration.

The P-FMA is a unique manipulator, combining the capabilities of significant dexterity, high tip forces, precise motion control, gear backdriveability, high end effector grip forces and torques, and the quality of flightworthiness. The 2.4-meter (8-foot) arm weighs 52.2 kilograms (115 pounds) and was delivered to NASA-MSFC in March 1977 for the integration of the remote controls. It is intended that the P-FMA would fly as a teleoperator experiment aboard an early Shuttle flight. Ultimately, it would be used on a free-flying spacecraft to extend the teleoperator capability to 5 kilometers (3.1 miles) beyond the Shuttle Orbiter.

This contract was performed under the cognizance of Messrs. John L. Burch and J. Dwight Johnston, Electronics and Controls Laboratory, NASA-MSFC. Specific acknowledgments for the work performed on this contract also go to the following Martin Marietta personnel:

Mechanical design - G. Kyrias, M. Snodgrass;
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1.0. Introduction and Summary

1.0 INTRODUCTION AND SUMMARY

The role of the remotely operated manipulator is expanding at a rapid rate, particularly in the area of earth orbital operations such as the assembly of large space structures, the performance of satellite retrieval and servicing, and other operations requiring the extension of man's reach in space. Under the direction of the NASA Marshall Space Flight Center (MSFC), Martin Marietta Corporation (MMC) Denver Division has designed, manufactured, tested, and delivered a seven-degree-of-freedom general-purpose manipulator arm which can be remotely operated in an earth orbital environment. The 2.4-meter (8-foot) *Proto-Flight Manipulator Arm (P-FMA)*, shown in Figure 1, combines the capabilities of significant dexterity, precise motion control, gear backdriveability, high tip forces, high end effector grip forces and torques, and the quality of flightworthiness. When integrated with the controls system being developed by MSFC, the manipulator will be capable of operation from a remote station such as the Shuttle Orbiter payload specialist station or a ground station.

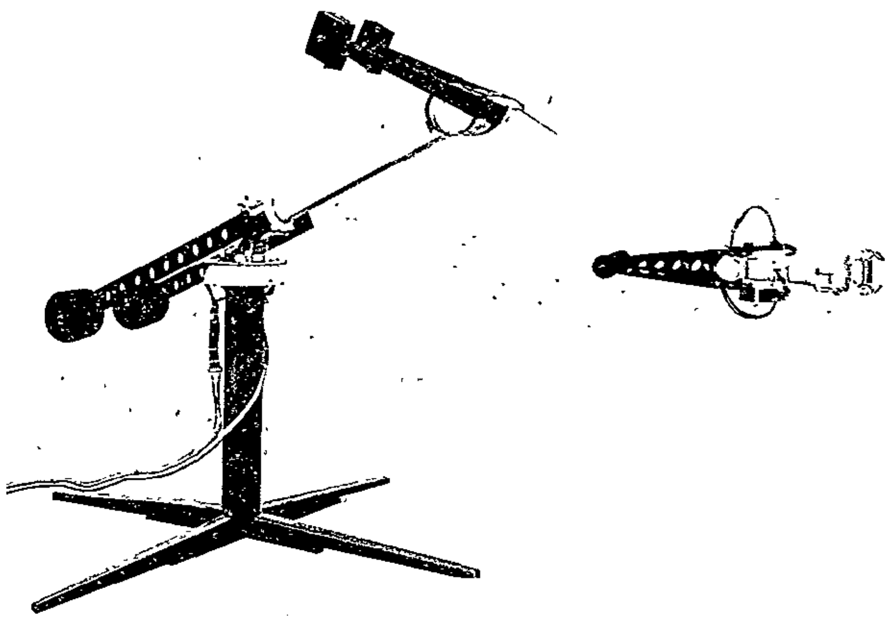


Figure 1 Proto-Flight Manipulator Arm

The P-FMA contract, NAS8-31487, was a 100 man-month activity conducted over a period of performance of 21 months. The contract technical specification, NASA-MSFC 50M23186, defined the manipulator arm requirements and served as the basis for the Contract End Item Specification, MMC No. CEI-PFM-00000, and the P-FMA Interface Control Document, MMC No. ICD-PFM-00000. These MMC documents are included in this final report as Appendices A and B, respectively.

The manipulator has a flight weight of 52.2 kilograms (115 pounds) and has an average power requirement of 250 watts with peak power of 500 watts. The unit is driven by providing an analog voltage to the motors to control the operational rate. The maximum supply voltage is 31V DC. A counterbalance is provided with the arm to permit the manipulator to perform useful tasks during laboratory testing and evaluations. This counterbalance is unbolted and removed to provide the flight configuration of the P-FMA.

The P-FMA drives will develop torques of 112 Newton-meters (90 foot-pounds) at the shoulder, 68 Newton-meters (50 foot-pounds) at the elbow, and 20 Newton-meters (15 foot-pounds) at each of the wrist drives. This capability provides tip forces in excess of 45 Newtons (10 pounds) in any direction at the end effector. The end effector has a controllable grip force of 45-400 Newtons (10-90 pounds) and a controllable torque up to 22 Newton-meters (16 foot-pounds), as well as continuous roll, in either direction. The drives can operate at an angular rate of 0.2 radians per second (11.5 degrees per second) at no-load and full load. Because of the precision of the drive joints, the starting torques are very low enabling minimum operating rates that are not perceptible to the eye. This results in the ability for fine positioning of the end effector to within a 1.3 mm (0.05 inch) tolerance.

The P-FMA drives were based on the design and experience developed by MMC during the development of a 3.7-meter (12-foot) arm, which was an internally-funded effort during the period of 1973-74. This arm has been used as a laboratory tool to develop various control modes and to evaluate orbital assembly operating techniques. The results of this experience permitted a rapid development of the new manipulator. Additionally, design improvements which were identified by this earlier experience could be incorporated into the proto-flight unit. Specific improvements included precision gearing, high quality motors and tach-generators, improved position feedback transducers (brushless sine-cosine resolvers), and supplier-adjusted fail-safe brakes. The P-FMA also has the following special flightworthy provisions incorporated in the design:

- Thermal coatings for passive thermal control in earth orbital operations;
- Low outgassing, flat viscosity index wet lubricant compatible with earth orbital environments;
- Space-compatible materials and processes;
- Demonstration of the drive design under thermal vacuum conditions.

Formal acceptance tests were performed on all drive joints to verify operational performance prior to final assembly of the P-FMA. These tests included torque and velocity performance, position accuracy measurements, and maximum travel. After final assembly of the manipulator, the acceptance tests included maximum reach, effective tip forces, electrical resistance and continuity, and end effector performance. A thermal vacuum test was conducted on one drive joint which demonstrated the operational performance capabilities at the temperature extremes of -73°C (-100°F) and 93°C (+200°F), as well as 93 hours of continuous operation.

The major conclusion from this contract effort is the demonstrated capability to produce a flightworthy manipulator that will perform useful work, as shown by the successful thermal vacuum tests and the development of 58-111 Newtons (13-25 pound) tip forces and end effector torques of 22 Newton-meters (16 foot-pounds) and grip forces controllable from 45-400 Newtons (10-90 pounds). It is our strong recommendation that NASA give consideration to our proposal of May 1976 for the development of a rate control system for the P-FMA. Only with the fully articulated controls can the utility of this general purpose manipulator be recognized.

The balance of this report describes the Engineering Design, Manufacturing, and Hardware Test activities conducted during the development of the P-FMA.

The final section provides conclusions and recommendations that should be considered in subsequent manipulator activities.

For the convenience of the reader, we have provided the following appendices to this report:

a) P-FMA Contract End Item Specification;

b) P-FMA Interface Control Document;

c) P-FMA Operations and Maintenance Document;

d) P-FMA Drawing Tree.

Detailed engineering drawings and "as-run" test procedures are on file at NASA-MSFC and Martin Marietta-Denver.

2.0 Engineering Design

2.0 ENGINEERING DESIGN

2.1 General - The P-FMA was designed to the requirements of the NASA technical specification, 50M23186. The resultant manipulator, as shown in Figure 2, has an effective length of 2.4 meters (8 feet), and with its seven degrees of freedom and articulation capability, is a general purpose arm. The unit was designed for stiffness and precise motion, which were accomplished by the proportional sizing of the drive joints and intermediate arm members, and the unique design of the drive gearing to minimize gear backlash. The arm will develop tip forces at the end effector of 58-67 Newtons (13-15 pounds) in the directions normal to the arm length, and can develop forces of 111-113 Newtons (25-30 pounds) in the extend/retract axis. The end effector can develop grip forces from 45-400 Newton-meters (10-90 pounds) and rotational torques up to 22 Newton-meters (16 foot-pounds) in either direction through the wrist roll.

The arm weighs 52.2 kilograms (115 pounds) in its flight configuration. The weight distribution is presented in Table 1. For laboratory operation, a

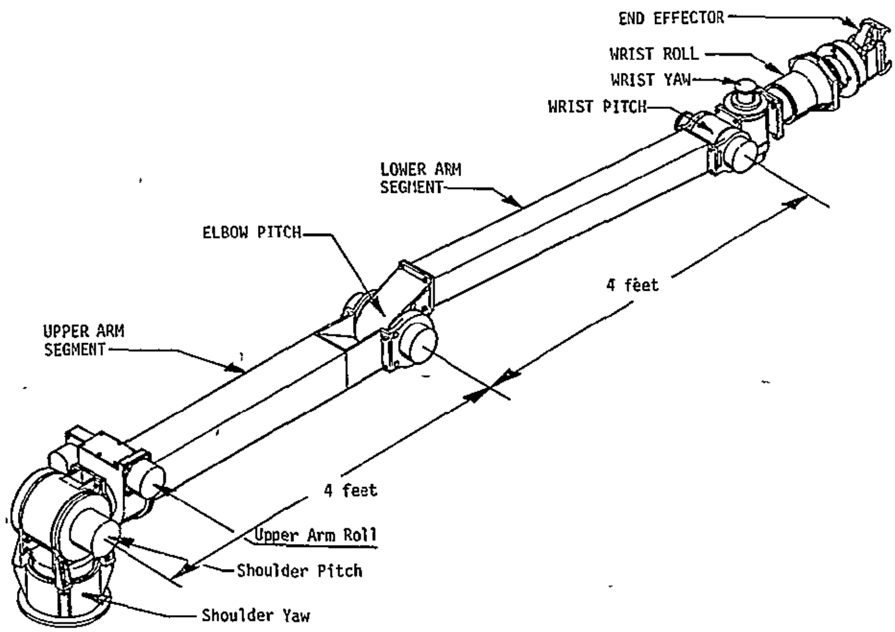


Figure 2 Proto-Flight Manipulator Arm (Isometric)

Table 1 Weight Distribution

Subassembly	Weight (lbs)
Shoulder Yaw	17.2
Shoulder Pitch	17.7
Shoulder Roll	12.0
Upper Arm	4.8
Elbow Pitch	11.0
Lower Arm	3.3
Wrist Pitch	6.5
Wrist Yaw	6.5
Wrist Roll	7.6
End Effector	5.4
Wire Harness + Bracketry	23.0
TOTAL	115.0

simple counterbalance has been applied to each of the three pitch axes. This permits the P-FMA to perform useful work during evaluations and testing under earth gravity conditions. The counterbalances are simply unbolted from the arm to obtain the flight configuration.

A *supply voltage* of 0-31V DC is required to operate the drive motors through the total performance range. The unit operates with an average *power requirement* of 250 watts and a peak power of 500 watts. The position transducers, which are sine-cosine resolvers, require single phase 400 Hz, 26V AC input voltage.

The arm is powered and controlled through two electrical connectors located at the base of the shoulder yaw drive. The *mechanical interface* is a bolt pattern of six 6.35-mm (1/4-inch) diameter holes equally spaced on a 19.0-cm (7-1/2 inch) diameter bolt circle.

The *dexterity* of the arm is demonstrated by its ability to touch its mounting base with the end effector. Figure 3 illustrates the maximum extent of travel of all drives. In order to stow the P-FMA for flight, the configuration shown in Figure 4 offers a low profile, with a small packaging envelope and good structural support.

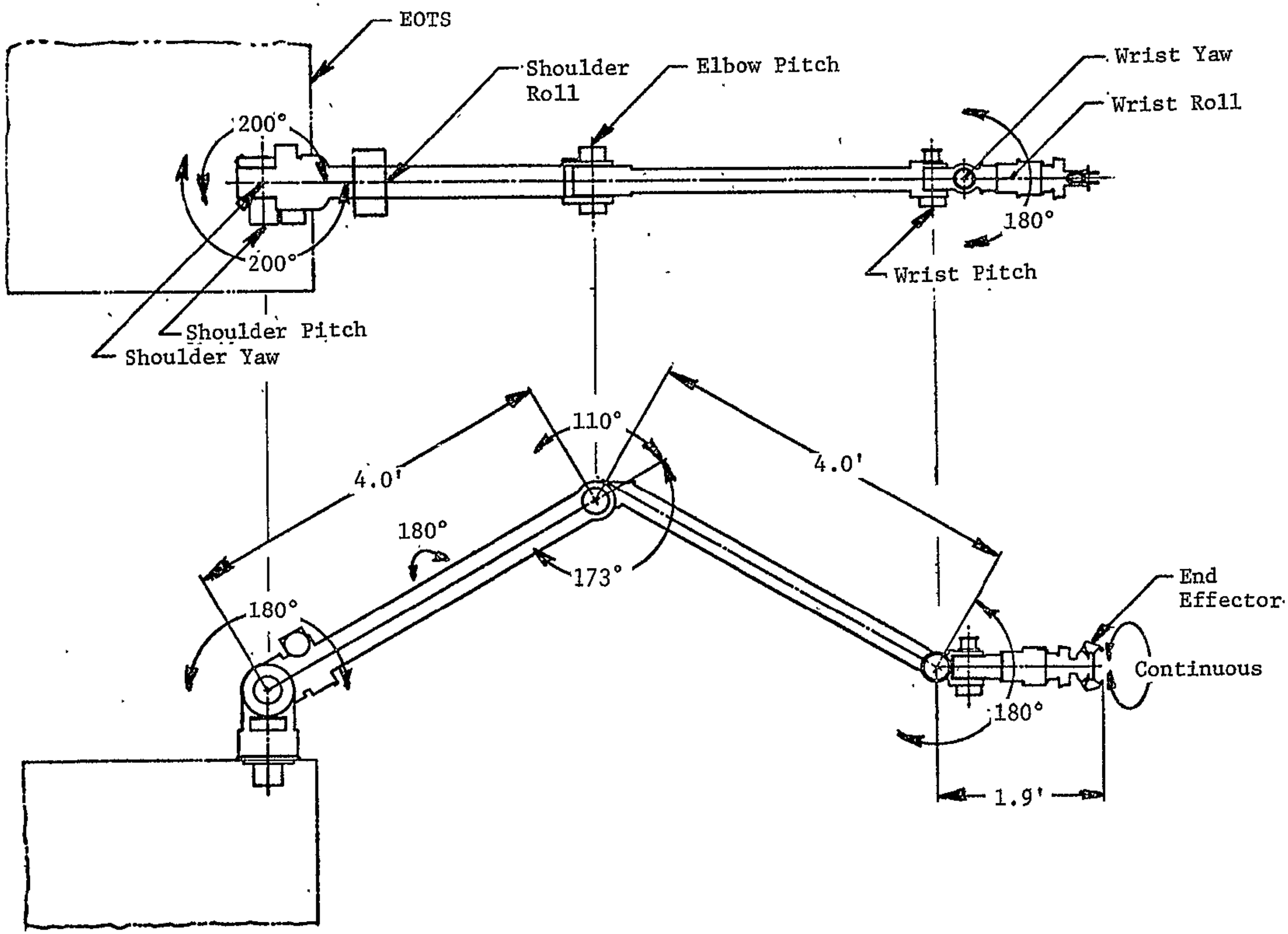


Figure 3 Maximum Travel

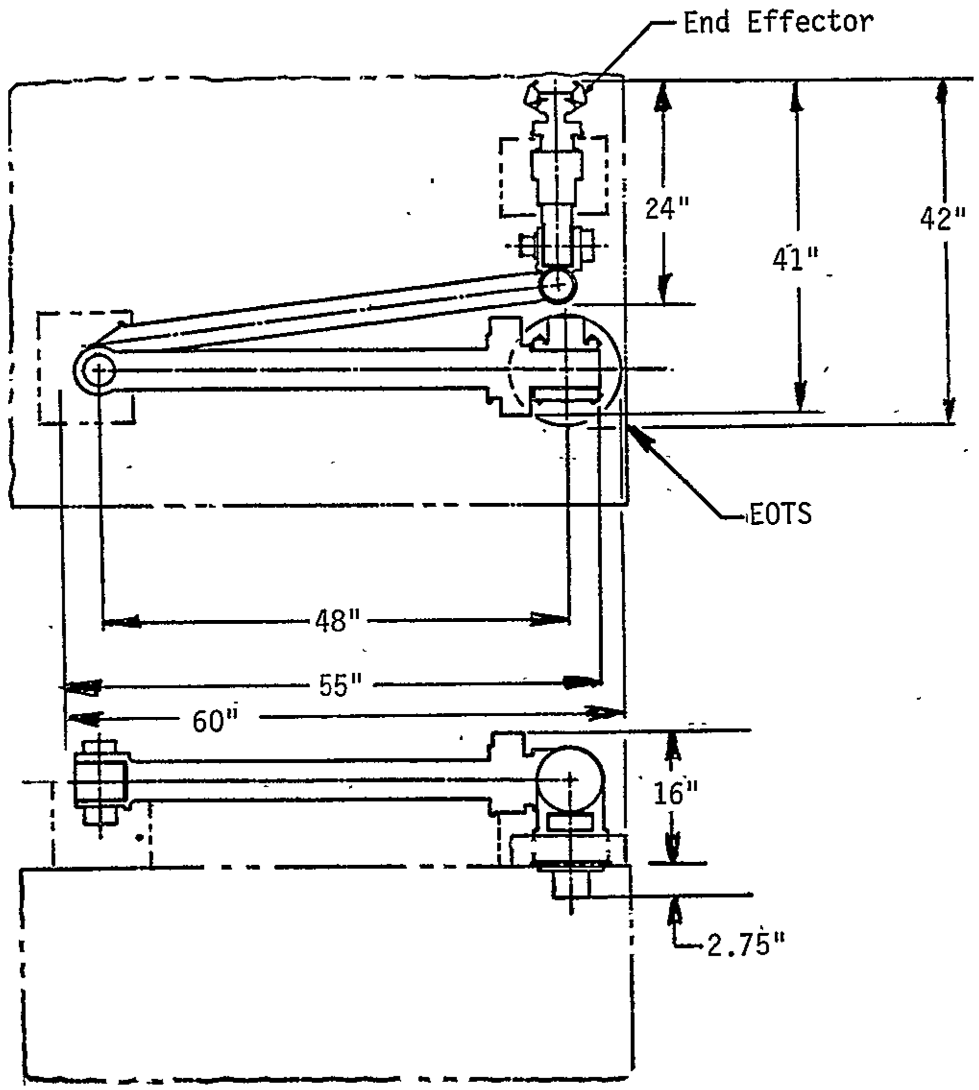


Figure 4 Stowed Configuration

All *components, processes, and materials* were screened and selected on the basis that they were *flightworthy*. Component suppliers were selected for their flight hardware experience. A materials list for the P-FMA was developed and forwarded to NASA. Material selections were taken from the NASA-MSFC Specification 50M02442, Revision W. Materials Usage Agreements (MUAs) were prepared for nonconforming materials.

Subsequent paragraphs of this section discuss the various detailed design descriptions of the drive joints, the end effector, and the analyses that supported the manipulator design.

2.2 Drive Joint Design - The P-FMA has seven degrees of freedom plus the end effector grip capability. Six of the drives (shoulder pitch and yaw, elbow pitch, and wrist pitch, yaw, and roll) are all of one typical design, but sized for specific torques and speeds as shown in Table 2. The seventh drive is the shoulder roll which is only for position indexing of the arm.

Table 2 Torque and Speed Requirements

	SHOULDER PITCH AND YAW	SHOULDER ROLL	ELBOW PITCH	WRIST PITCH, YAW AND ROLL
Drive Torque ft-lbs (max)	90	INDEXING ONLY	50	15
Weight - lbs	17.75	10.32	11.5	6-pitch and yaw 7-roll
Gear Reduction	109.8:1	66:1	103.1:1	86.4:1
Motor RPM (no load)	208.62	72.60	391.78	164.16
Output RPM (no load and full load)	1.9	1.1	3.8	1.9

The *basic drive joint design* is shown in Figure 5. The drive is powered by a pancake torque motor mounted on Shaft 1. The shaft 1 pinion drives a dual mesh, three-stage gear reduction. This gear train can be traced by following the torque transmission through Shafts 2 and 3, inclusive of Sections A and B. The final gear stage terminates with the internal gear which is fixed to and drives the outer housing. The tachometer (rate sensor) is mounted to the shaft 1, giving the maximum voltage for rotational speed. The fail-safe brake is also mounted on the Shaft 1 which requires the minimum torque, and therefore minimum power to restrain the drive if motor power were interrupted. The resolver (position sensor) is driven through an anti-backlash gear from Shaft 3.

The *precision* of the drives is accomplished by the use of AGMA Class 12 spur gears and the incorporation of an adjustment in the second gear mesh to remove the system backlash. This is illustrated in Figure 6. Prior to doweling the adjustable gears, the gear train backlash is removed by rotating all gears until the tooth faces are in contact. This design results in a total gear backlash of less than one arc minute.

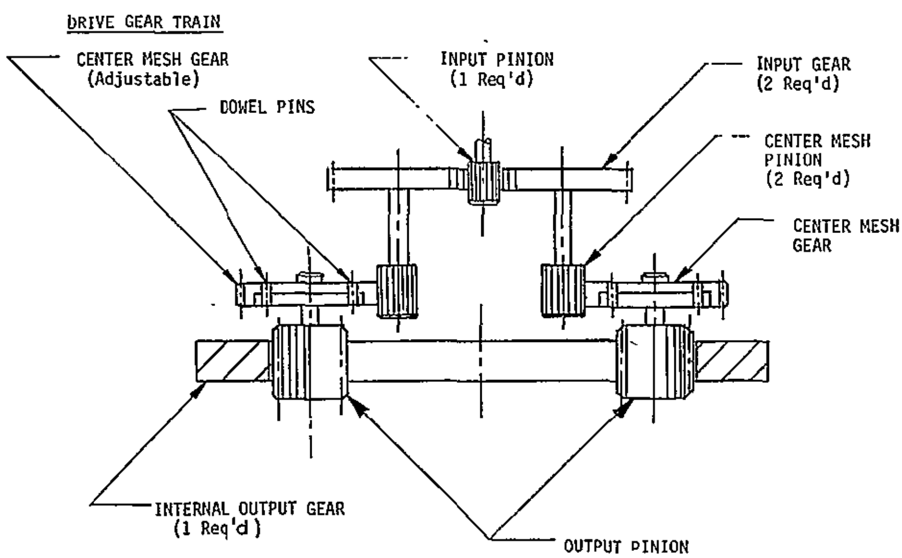


Figure 6 Drive Gear Train

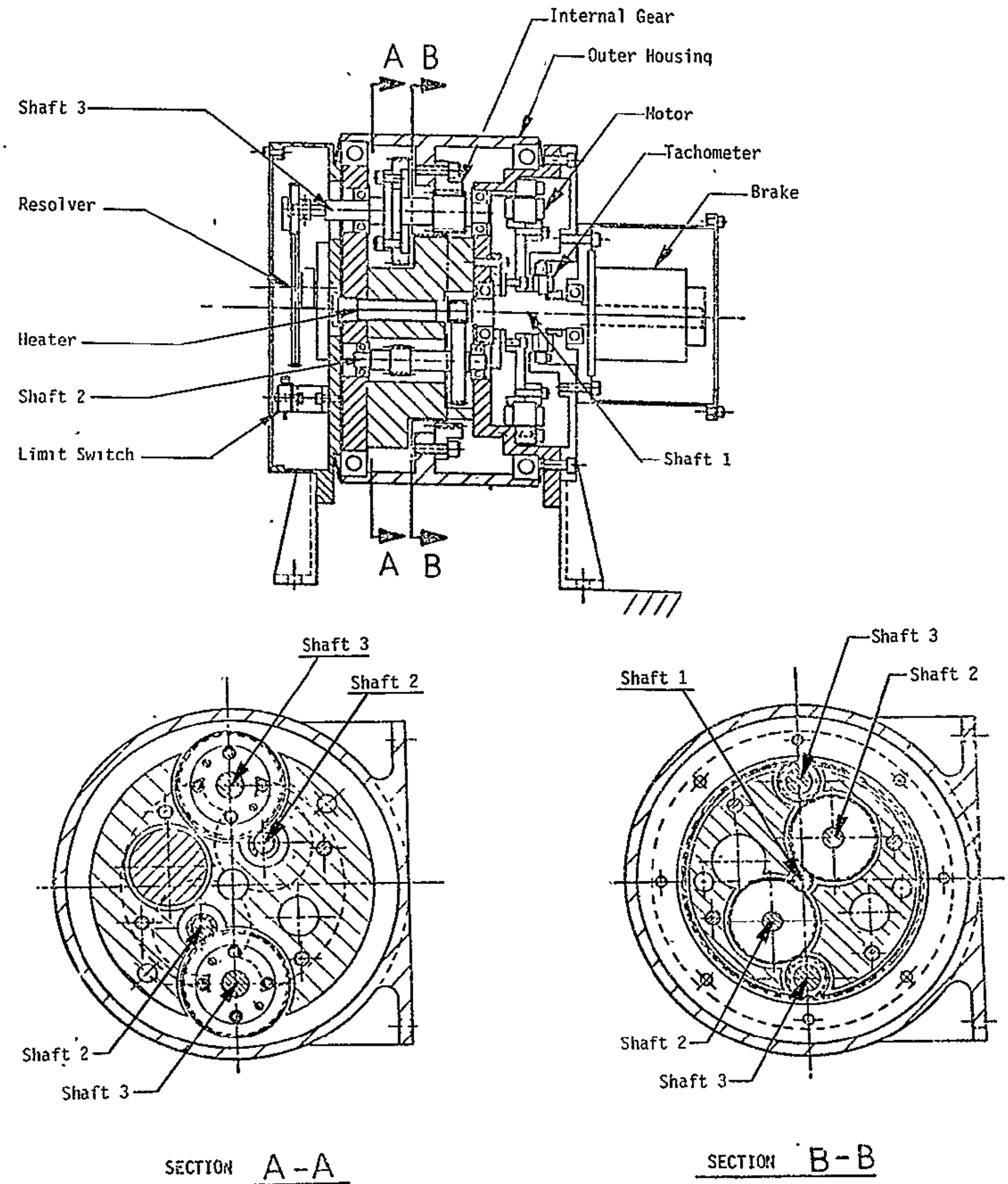


Figure 5 Drive Joint Design (Typical)

These drive joints have the feature of *backdriveability* because of the inherent efficiency of a spur gear train. With no power applied to the motor and external forces applied to the output side of the drive, the drive will rotate, thus preventing damage to the unit due to overloading by external forces. This feature becomes useful when performing close tolerance work such as inserting of a pin in a hole which has misalignment. Once the pin has been started into the hole, the motor input signal should be zero on the wrist drives. Power properly applied to the shoulder and elbow pitch drives will provide a translational motion to the end effector and the three wrist drives will backdrive to eliminate the misalignment. If the backdrive rotation is not required, motor input signals would be applied to the drive.

The *fail-safe brakes* are designed to be applied in case of power failure; each brake is released when powered. The brakes have been sized to restrain the rated torque of the drive, but will slip at 15 percent over rated torque. Therefore, overloads will not damage the gear train; and in case of a flight anomaly, the arm could be repositioned to the stowed configuration either by EVA or use of the Shuttle attached manipulator system.

A *limit switch* is provided in each drive, except for the wrist roll, to provide an indication that the drive has reached its maximum travel. The *heaters* are required in the cold thermal case to prevent the drive temperature from going below -73°C (-100°F). Temperature sensors are provided in all three of the pitch drives. An eight (8) conductor *slip ring assembly* is incorporated in the continuously rotating wrist roll drive for the end effector operation. A listing of the major component suppliers is presented in Table 3.

Figure 7 is a section view of the shoulder roll drive which is used only for position indexing. This is a worm drive with the resolver worm and the motor on the same shaft. The worm drive provides a nonbackdriveable condition and therefore no brake is required. The limit switch and heater serve the same functions as in the other drives.

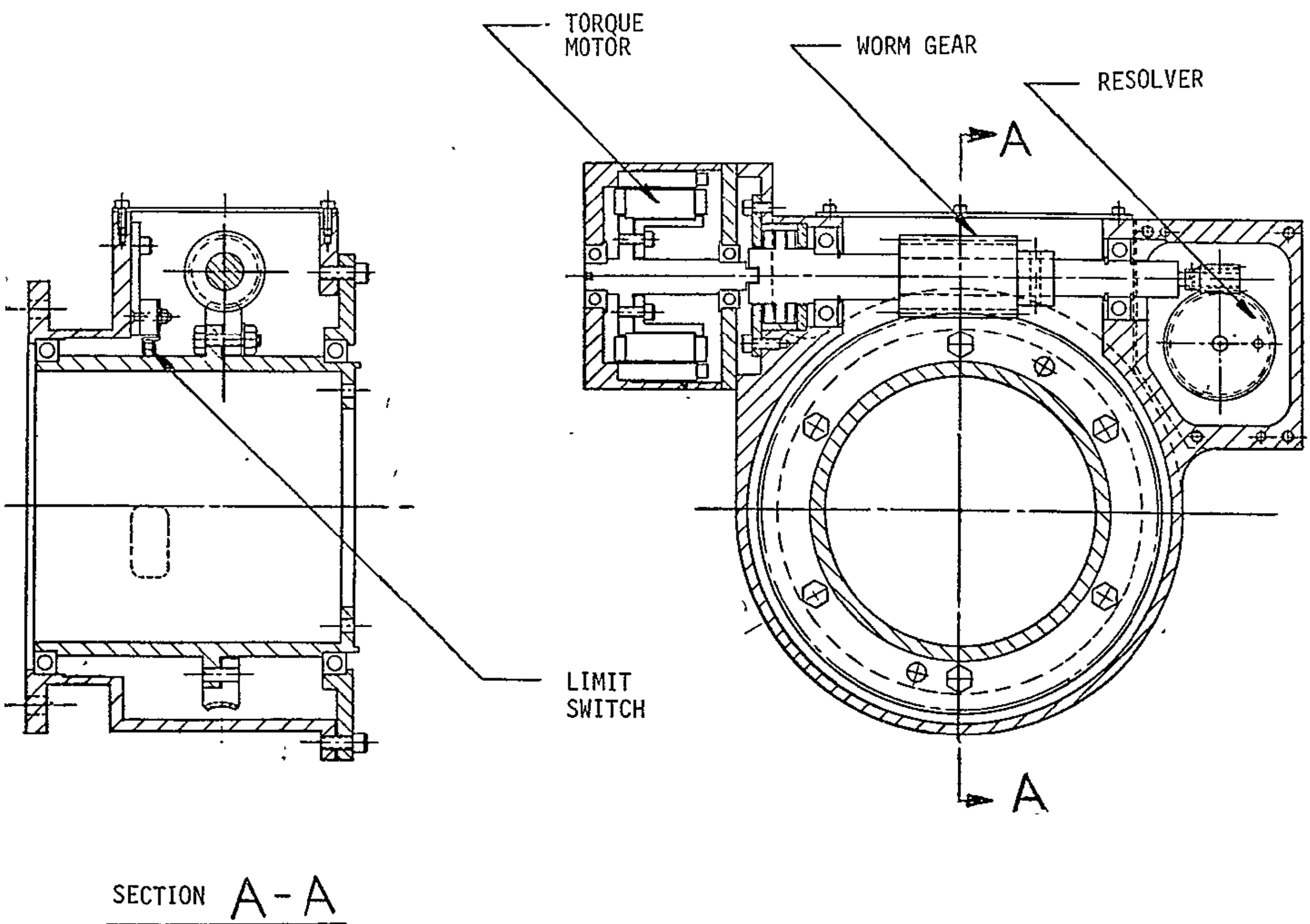


Figure 7 Shoulder Roll Joint Design

Table 3 Component Suppliers

COMPONENT	MANUFACTURER	ADDRESS
Motor	Inland Motor	Radford, Virginia
Tachometer	Inland Motor	Radford, Virginia
Resolver	Singer-Kearfott	Clifton, New Jersey
Gears	Schwartz Precision Gear Co.	Warren, Michigan
Fail-safe Brake	American Precision Inc.	East Aurora, New York
Heater	Watlow Electric Mfg. Co.	St. Louis, Missouri
Temperature Sensor	Hy-Cal Engineering	Santa Fe Springs, California
Limit Switch	Honeywell, Inc.	Freeport, Illinois
Slip Ring	Polyscientific Division Litton Precision Products, Inc.	Blacksburg, Virginia
Electrical Connectors	ITT-Cannon	Santa Ana, California
Wiring	W. L. Gore, Inc.	Flagstaff, Arizona

The drives are lubricated with a *wet grease lubricant.* A lithium-based grease (P-L Scientific L-11) with a small fraction of molybdenum disulfide has been used on all drives for ground based operations. For space operations, the unit has been tested with a *Braycote* 3L 38-RP lubricant. This grease was selected for its low outgassing and flat viscosity index. The selection of a wet lubricant over a dry-film or solid lubricant was based on the high contact stresses in the bearings, and the probability of high humidity exposures to prelaunch and post-landing environments. However, all drives are assembled with teflon dust seals at the interface between the fixed and rotating housings of the drive.

Each motor and tachometer is provided with a *spare brush ring assembly.* For laboratory operations, the standard silver-graphite brushes are installed. Prior to vacuum environment (testing or space) operations, the brushes are removed and replaced with *Boeing compact* 046-45 brushes.

Special considerations were given to the *thermal design* of the drives. The operational thermal limits are established by the lubricant viscosity on the cold extreme and the motor rotor temperature on the hot extreme. The drives were biased in the direction of the cold case which provides for longer operating time at a motor-stalled condition. To accomplish this biasing, the exterior of the arm was coated with a white acrylic lacquer ($\alpha/\varepsilon \approx 0.3$) and internal surfaces

c. Motor rotor/stator interference - The design clearance is reduced by 35 percent at a maximum rotor temperature of 155°C (311°F). This is an acceptable condition.

The mechanical components of the drives were structurally analyzed as described below.

a. Gear analysis - Each gear mesh of each drive was analyzed to determine both strength and durability horsepower. Techniques were based on American Gear Manufacturers' Association (AGMA) methods. Significant margins (> 100%) existed in all cases, as shown in Figure 9. Gear tooth load cycles and contact stresses were computed for the pinion of each drive for comparison with lubricant allowables. Based on the drive operating for 500 hours in each direction of rotation, gear life was acceptable even using some dry-film lubricants, if special precautions were taken with application and maintenance. Extremes showed 23 x 10^6 contact cycles

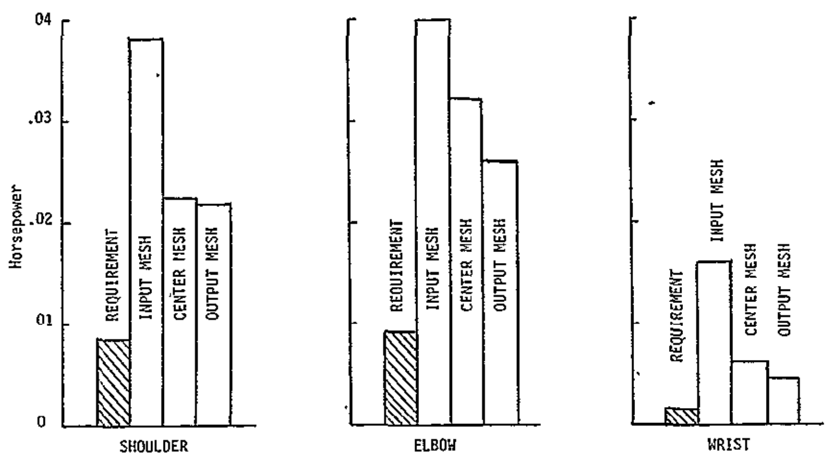


Figure 9 Gear Durability Horsepower

at no-load, and at full stall (0 cycles) a contact stress of 1.0×10^6 kilograms/sq cm (145,000 psi).

b. Bearing loads analysis - Radial bearing loads were predicted based on stall torque, no friction, and equal distribution of loads between the dual gear sets. Adequate margin existed for both static and dynamic bearing capacity, as shown in Figure 10. However, calculated contact stresses at the maximum rated horsepower showed a value of 1.9 x 10 kg/sq cm (270,000 psi) which exceeds the acceptable limit for dry-film lubricants. It was primarily this data that resulted in the selection of a wet lubricant for the drive joints.

c. Vibration analysis - In order to provide data for the servo-control design, the natural frequency of the P-FMA was computed at its fully extended configuration with tip loads of 0, 50, and 136 kilograms (0, 110, and 300 pounds). Under these conditions the natural

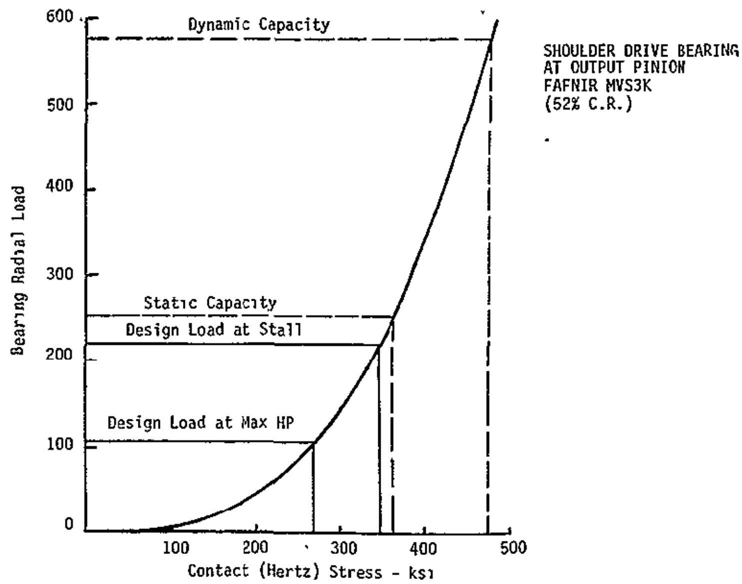


Figure 10 Bearing Load/Stress Curve

frequency was 2.4, 0.9, and 0.6 Hertz, respectively. The natural frequency of our in-house manipulator with no tip load was 0.7 Hz, and the controlled performance of this arm is well documented.

2.5.2 Thermal Analysis - The thermal analysis was performed in two phases--1) analysis of a drive joint to determine the thermal design requirements, and 2) analysis of the total arm to determine the overall temperature extremes and the adequacy of passive thermal control. The Martin Thermal Radiation Analysis System (TRASYS) computer program was used to calculate radiation interchange and external heat rates. The Martin Interactive Thermal Analysis System (MITAS II) was used for the thermal network solution.

The thermal environments were based on a 400 km (250 mile) circular orbit. The basis for the cold thermal case was an equatorial orbit with the manipulator in the stowed configuration on a free-flying vehicle, which was tilted at 45 degrees to the orbital plane. This orientation simulates no direct solar exposure, and always oriented toward the earth. The hot thermal case has the manipulator in a deployed configuration on a free-flying vehicle and in a circular polar orbit. This orientation permits planetary and albedo heating as well as direct solar exposure.

The wrist pitch drive was selected for thermal analysis because the wrist drives represent the smallest thermal mass and the pitch drive has an internal temperature sensor which is useful during thermal tests. Seven thermal cases were identified based on the orbital attitude, operational and nonoperational drive joint, operational and nonoperational heater, and transient operations. The conclusions from this drive joint analysis were:

a. Provide a high emissivity exterior surface such as white acrylic lacquer, which will cold bias the drive in all space environments. This will enable a maximum continuous operating time since the motor rotor temperature is a design limit.
b. Provide black anodized interior of the drive housing to increase motor heat rejection and aid in the warming of other internal drive components.

c. Provide a small heater for each drive to prevent drive temperatures from dropping below -73°C (-100°F).

The resultant drive temperature extremes are presented in Table 4. The steady state temperature distribution for the P-FMA for the cold case (only heaters "on") and the hot case (all components operating continuously) is shown in Table 5.

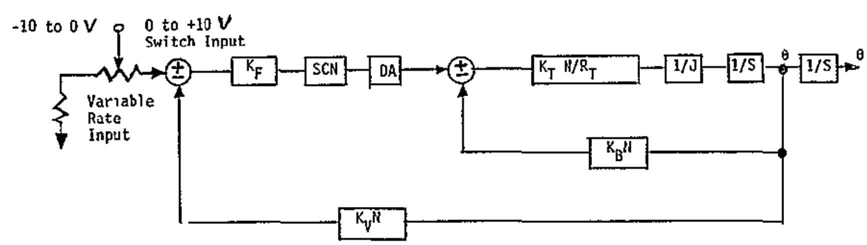
Table 4 Extreme Drive Joint Temperatures

DRIVE ELEMENT	TEMPERATURES (°F)	
	Cold Case	Hot Case
Housing	-44	81
Resolver Cover	-65	43
Brake Cover	-61	49
Motor Rotor	- 1	310*
Pinion Gear	0	151
*8.9 minutes of running; start temperature 100°F		

2.5.3 Rate Control Analysis - The Proto-Flight Manipulator Arm (P-FMA) controls analysis was performed based on the rate servo loop as shown in Figure 11, which is intended to demonstrate the operation of each drive joint. The control laws and articulated arm control design are being developed by NASA-MSFC. The results, which are summarized below, provided the parameters for bidirectional motion at variable input rates and showed the stability and bandwidth for drive joint operation. The control parametric values are tabulated in the P-FMA Interface Control Document (Appendix B to this report). The controls analysis was performed in the following manner.

Table 5 P-FMA Temperature Distribution

Arm Subassembly	Temperatures (^0F)		
	Cold Stowed	Cold Deployed	Hot Deployed
Shoulder Yaw	-15	-12	136
Shoulder Pitch	-17	-25	137
Shoulder Roll	-73	-102	95
Upper Arm	-65	-111	93
Elbow Pitch	4.3	-18	114
Lower Arm	-59	-105	105
Wrist Pitch	-11	-18	125
Wrist Yaw	-15	-14	139
Wrist Roll	-15	-19	139



DEFINITIONS

K_T = torque sensitivity of motor, ft-lb/amp
N = gear ratio
R_T = total resistance, ohms
J = total reflected inertia, ft-lb-sec^2 (loaded and unloaded)
K_B = back EMF of motor, volts/rad/sec
K_V = tachometer sensitivity, volts/rad/sec
K_F = forward loop gain
SCN = servo compensation network
DA = drive amplifier

Figure 11 Rate Control Loop

a. Drive motors were selected on the basis of stall torque and no-load speed. This established the torque sensitivity (K_T) and the back-EMF (K_B), and determined the damping factor (F_I).

b. The tachometers were selected based on the speed range of the motors. Since the tachometer and the motor are mounted on a common shaft, the maximum tachometer signal level could be attained with no additional complexity to the drive design. The tachometer sensitivity (K_V) of 0.118 volts/radian/second was selected for all drives.

c. Drive joint inertias (J) were calculated, based on the final joint designs. Arm inertias were also calculated for the unloaded and loaded conditions, in a typical deployed configuration. Additionally, a maximum inertia was calculated with the arm in a fully extended configuration, with and without the maximum 50 kg (110 pound) tip load.

d. Drive amplifier gains ($K_F K_{DA}$) were calculated for each of the drives and are listed in Table 6. The following factors were considered:

   1) The maximum controller input was assumed to be 10 volts.
   2) Drive breakaway torques were determined to be insignificant.
   3) System compliance values were assumed to be 20,300 Newton-meters/radian/second (15,000 ft-lbs/radian/second) for the shoulder drives, 10,800 Newton-meters/radian/second (8,000 ft-lbs/radian/second) for the elbow drive, and 2,700 Newton-meters/radian/second (2,000 ft-lbs/radian/second) for the wrist drives. These values were determined from our in-house controls development.
   4) The damping factor (F_I) is 0.1 of an infinite impedance power source.

e. Open loop bode plots were generated for each of the drive joints to demonstrate that with the drive amplifier gains of Table 6 and the correct servo compensation networks, each drive has sufficient

Table 6 Drive Amplifier Gains (volts/volt)

SY	SP	EP	WP	WY	WR
492	492	1003	382	382	382

response and phase margin for both no load and full load. They also proved that the joint designs, in particular the motor selection, will easily meet specification requirements and even provide growth potential for loads and/or response. The compensation and gains were selected to provide one set of values for both load and no load for each of the joints. The 3 Hertz bandwidth response requirement has been met for the unload condition only as a cost effective measure to simplify control electronics.—More optimum performance can be achieved if the user wishes to vary the gains and compensation values.

f. To provide added flexibility to the user, position sensors (brushless resolvers) have been incorporated into each drive joint. The resolvers are driven through anti-backlash gears from the final output stage to minimize position error due to gear backlash.

Resolvers were selected in preference to encoders for the following reasons:

a. The resolver weight and volume were compatible with the drive sizes.

b. An encoder at each drive would significantly increase the size of the main wire harnesses due to the significant increase in number of wires required.

c. The encoder was not compatible with the environmental temperatures unless special heaters were provided.

2.5.4 Failure Modes and Effects Analysis (FMEA) - A failure modes and effects analysis was performed in accordance with NASA-MSFC document SE-020-006-2H, *Guidelines for Performing FMEA on the Solid Rocket Booster*, dated 10 July 1975. This analysis verified there were no failures that would jeopardize crew safety or primary mission objectives. An extension of this analysis presents the resultant reduction in reach envelope under various drive joint failures. The most severe failure would be that of the elbow drive. Preceding the FMEA, we performed a *failure mechanisms analysis*, which basically catalogued the causes of failures and identified the techniques to minimize the failure occurrences. Analysis tables were developed for the following:

- DC Torque Motors
- Tachometers
- Spur Gears
- Worm Gears
- Ball Bearings
- Resolvers
- Lubricants

Additionally, *failure probability analyses* were performed for the motors and tachometers, resolvers, and the slip ring.

2.6 Counterbalance Design - The P-FMA was designed for operation in a zero-g environment. A *simple bolt-on counterbalance* was provided for each of the three pitch axes in order to permit useful operations in the laboratory environment while not degrading the flightworthy quality of the arm. Thus, the arm can perform useful work during laboratory evaluations and testing. Additional counterbalance weights have been provided for the condition when simulated loads are applied to the end effector. Each of the three pitch drives must be sequentially counterbalanced to accommodate the increased tip load. When properly adjusted, the arm can be positioned throughout its full range of travel in shoulder yaw and all pitch motions, as long as the shoulder roll drive is in its nominal position. If the shoulder roll is rotated, the wrist yaw becomes a pitch degree of freedom and is not counterbalanced. With nominal operations, the wrist yaw also produces an imbalance error when the drive is actuated, as shown in Figure 12. Wrist yaw travels of ± 20 degrees have an insignificant imbalance, but if the travel is greater counterbalance compensation should be considered.

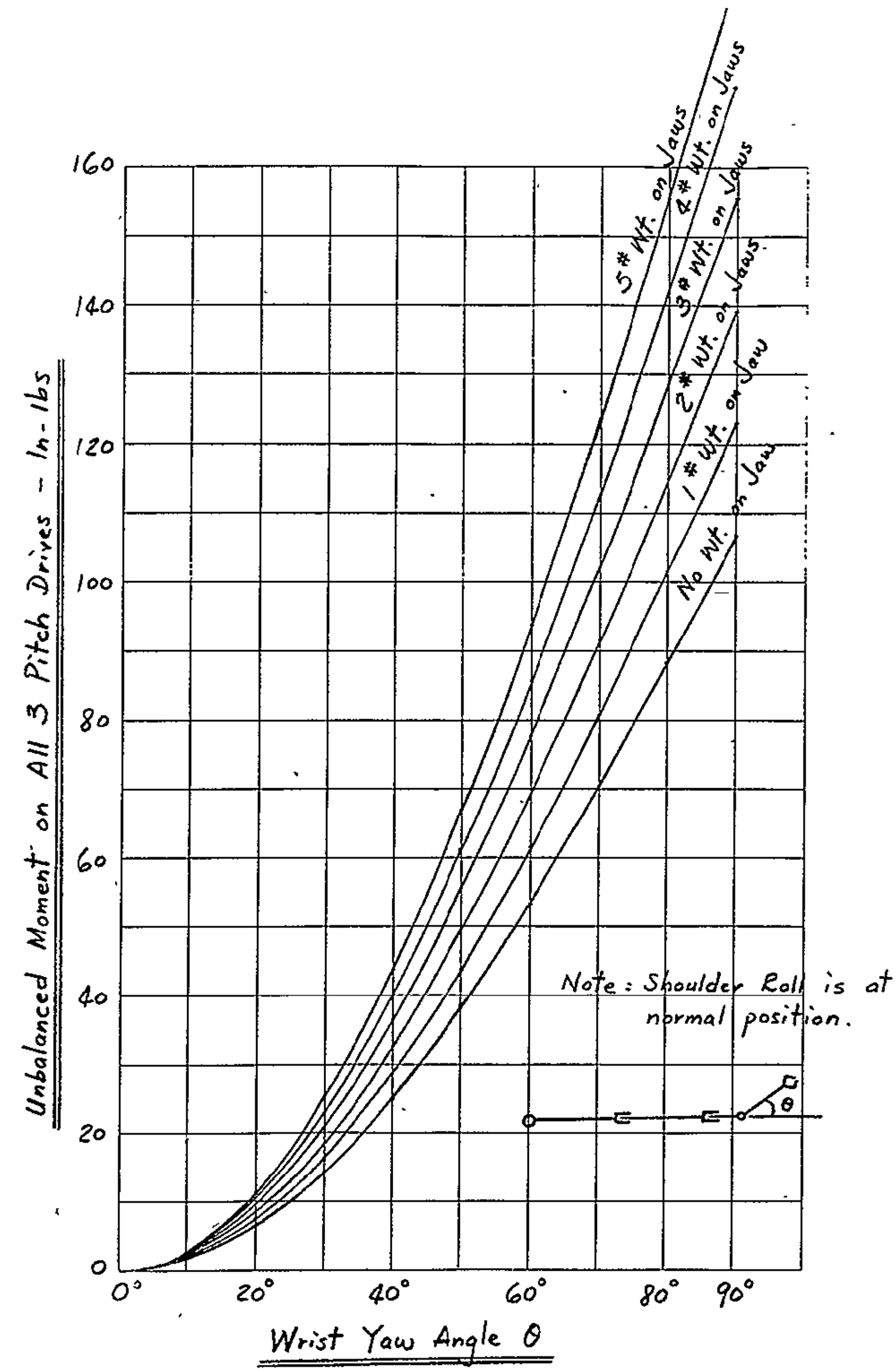


Figure 12 Counterbalance Error

All changes to the counterbalanced condition should be carefully planned and analyzed before implementation. After implementation, tests should be conducted with the arm manually supported as the individual drive brakes are released. Operations at minimum drive voltages, running in each direction at the same voltage, will demonstrate an effective counterbalance.

In the design of the control system it must be recognized that the counterbalance causes a large increase in the reflected moments of inertia on the drives. Accelerations will be significantly decreased, thus reducing the control response. If the manipulator is ground tested with the counterbalance--controlled by a closed position loop--extreme care must be taken so the added inertias do not cause instability that could damage the drives.

3.0 Manufacturing

3.0 MANUFACTURING

3.1 General - The manufacturing of the P-FMA was conducted in four phases--1) procurement of components, 2) detail manufacturing, 3) assembly of drives, and 4) final assembly of the arm. Figures 13, 14, 15, and 16 show the P-FMA in the various phases of manufacture.

The manufacturing period of performance was held to a minimum by the effective use of the Engineering Model Shop which permits daily liaison between the manufacturing and engineering personnel. From this same location, quality assurance inspections are conducted and documented. Corrective actions and drawing revisions can be immediately resolved and implemented. We have demonstrated the cost-effectiveness of manufacturing and assembly of limited quantities of units by this method. Subsequent paragraphs of this section discuss the manufacturing phases in detail.

3.2 Procurement of Components - During the design phase of the P-FMA program, components had been selected by trade studies which considered performance, geometry, supplier qualifications, and cost. Procurement activities were started with the issuing of statements of work for competitive bidding for the various P-FMA components. In most cases the statement of work identified manufacturers' part numbers, but required space-worthy materials and process controls, as well as quality assurance provisions and documented functional acceptance tests prior to shipment. In some cases such as gears, brakes, and resolvers, there were no catalogue equivalents available. Therefore, these statements of work also included detailed drawings and special testing requirements. In the case of the resolvers, two sizes were required; one size had been developed as well as the technical design principle.

The final selections of components and suppliers were mutually established by NASA and Martin Marietta at the Critical Design Review. Firm priced procurement agreements were issued to the selected suppliers. Issued dates were based on program need dates with a 30 percent margin and were influenced by contract incremental funding limitations. Supplier performance was quite satisfactory

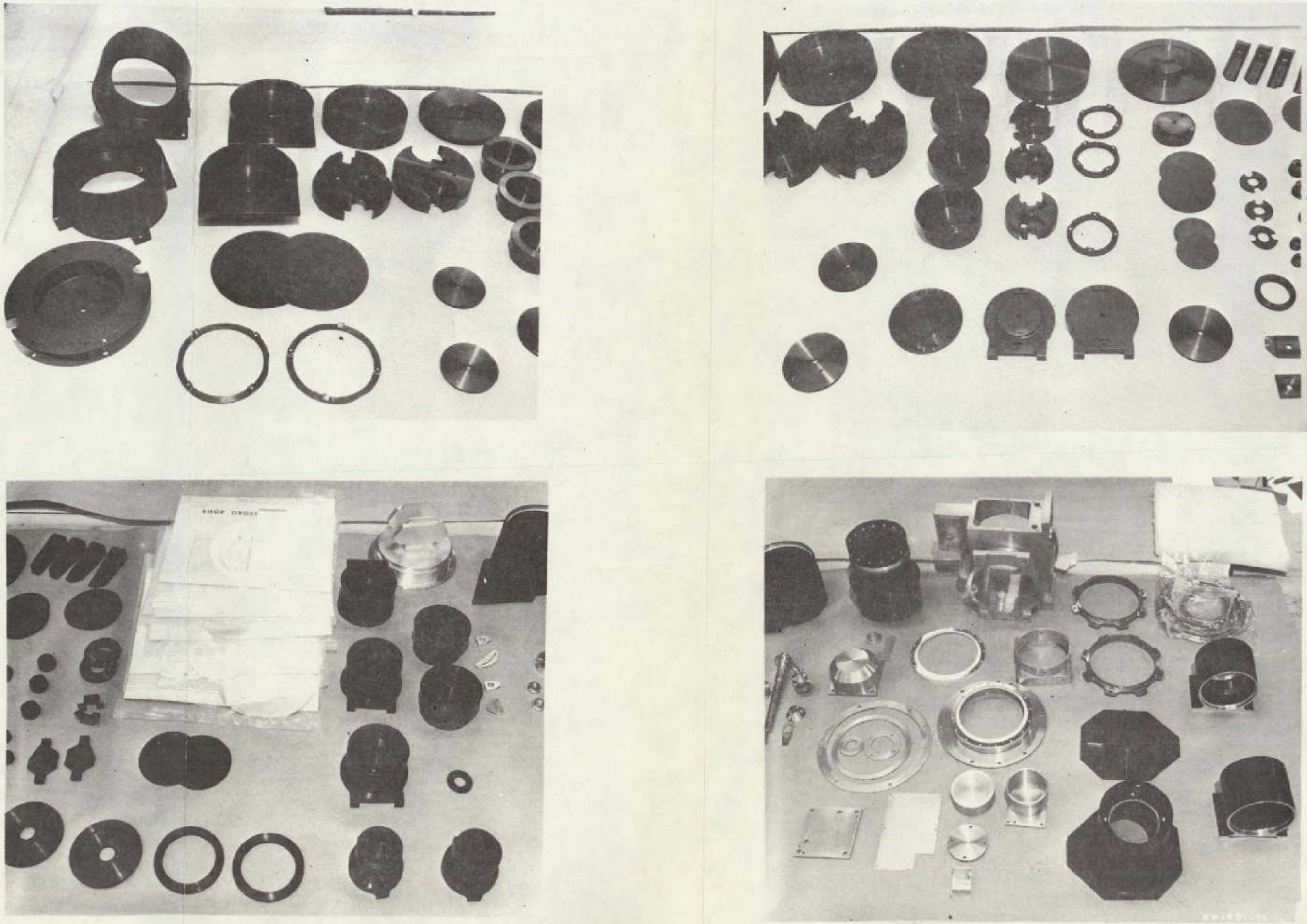


Figure 13 Machined Details

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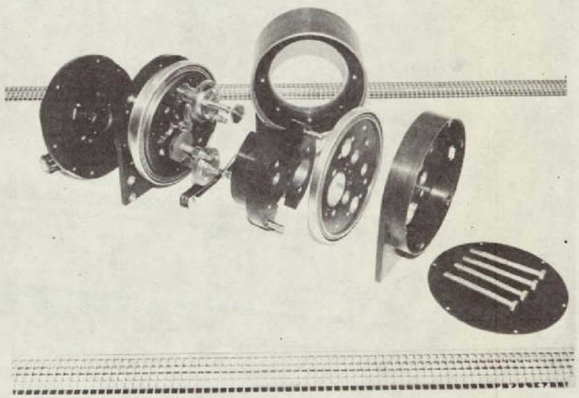

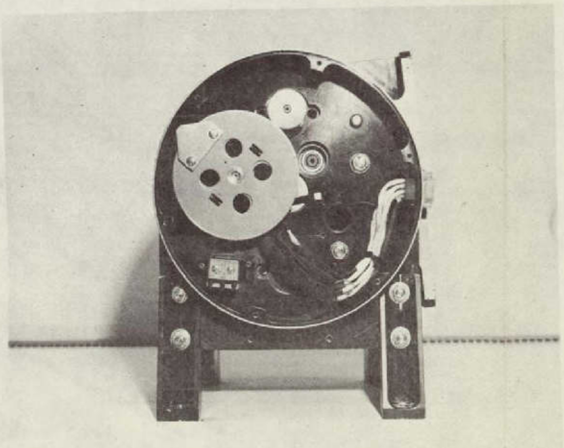

Figure 14 Drive Joint Assembly

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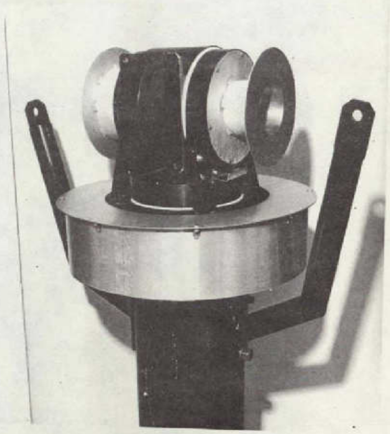

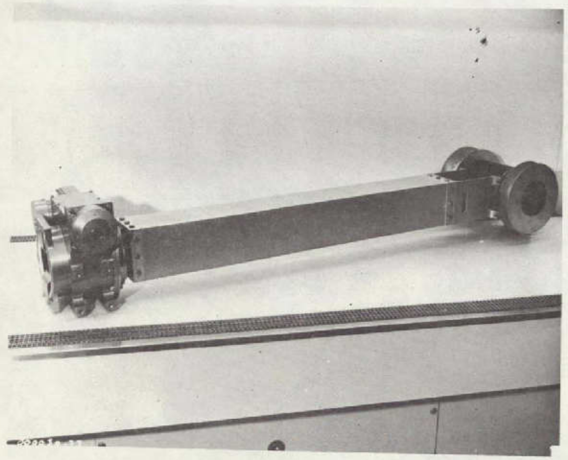

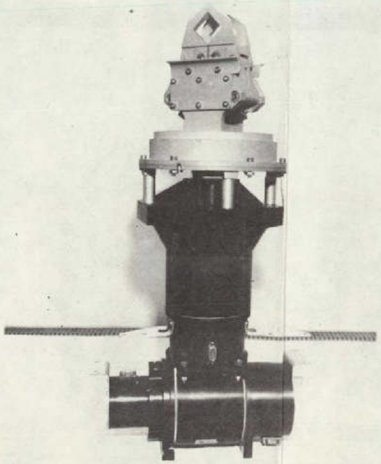

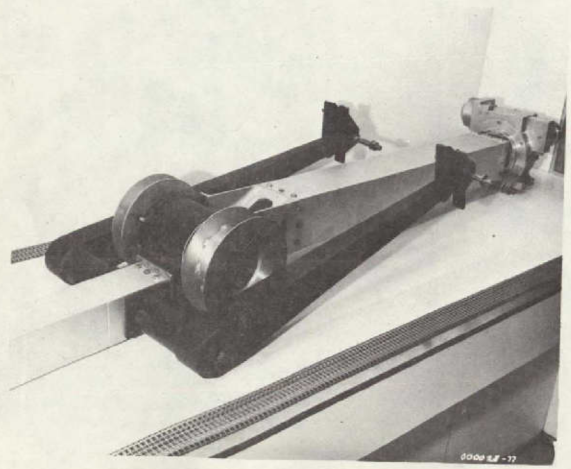

Figure 15 Start of Final Assembly

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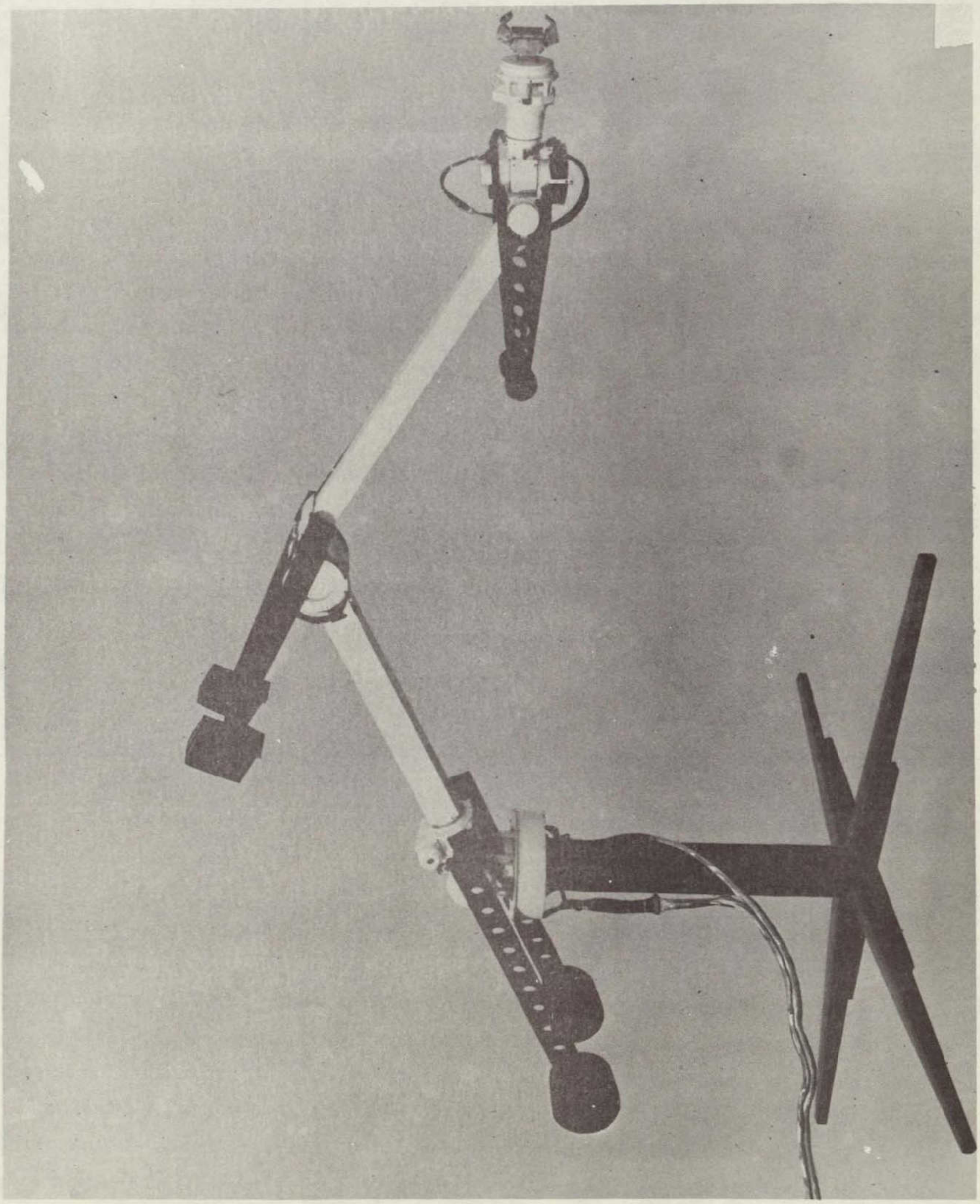

Figure 16 P-FMA as Delivered to NASA

despite some technical problems which were resolved without the reduction of technical performance. A listing of the primary components and suppliers was shown in Table 3.

3.3 Detail Manufacturing - Because of design similarity of the two shoulder drives and the three wrist drives, many machined details were made from a common machine setup in order to improve productivity. Details were rough-machined then brought to final external dimensions. In order to incorporate precision into the drives, final gear shaft centers and bearing diameters were located and finally machined, using jig bore precision within ± 0.005 mm (± 0.0002 inch). All specified details were then black anodized as required for passive thermal control. By completely anodizing these parts, significant time otherwise required for masking was saved. Subsequently, the external finishes were easily applied. The upper and lower arm segments were manufactured from standard square extruded aluminum tubing. The wall thicknesses were reduced internally by chemical milling to reduce weight and still maintain a maximum cross-sectional moment of inertia. Machined details were inspected for dimensional compliance to engineering drawings.

3.4 Assembly of Drives - All drive assembly operations were performed on laminar flow benches within a clean room. All parts had been previously cleaned. Bearings were cleaned ultrasonically prior to being lubricated. The initial assembly phase involved the installation of gears and bearings into the center internal housing. All bearings were installed with a light "push" fit. The two adjustable gears were located and doweled to minimize the gear backlash. At this point, two interim acceptance test points were verified by Quality Assurance to document the measured gear backlash and the static torque for each drive. These tests are described in the hardware testing section under paragraph 4.4.1. At this point, component installation and electrical wire routing were performed concurrently. The motors with matching brush ring assembly are installed on the input shaft. The tachometers with matching brush ring assembly are then installed on the same shaft. The fail-safe brake is installed with its housing and cover to complete one side of the drive. On the other side of the unit, the heater and temperature sensor (pitch drives only) are installed. A thermal conductive grease is used for improved heat transfer. The resolver and associated anti-backlash gearing is installed, coming off the final output pinion shaft. The resolver housing or cover is then installed. As components are installed they are wired in accordance with engineering schematics and wiring diagrams. Each drive has two main connectors--one for power conductors and the other for instrumentation conductors--mounted to the fixed portion of the drive housing. These connectors will subsequently be mated with the respective main wire harnesses during final assembly.

At this point, further interim acceptance tests are conducted to verify electrical continuity and resistance, and the functional performance of each drive. These tests are further described in the hardware testing section under paragraph 4.4.1.

The drive assembly procedures for the shoulder roll and the end effector are different due to their unique designs. However, the assembly philosophy and subsequent tests are similar.

Just prior to final assembly of the P-FMA, final external thermal finishes were applied to the drives, tubular arm segments, and wire harness bracketry. It should also be noted that the wrist pitch drive was subjected to the thermal vacuum qualification testing, including a 93-hour operational life test, after the functional acceptance tests. Following the qualification tests, the unit was completely disassembled, inspected, relubricated, reassembled, and re-acceptance-tested prior to final assembly into the P-FMA.

3.5 Final Assembly - The final assembly of the arm progressed, starting from the shoulder yaw drive to the shoulder pitch and so on throughout the length of the arm. As the drives were installed, the main wire harnesses were developed, routed, and clamped in accordance with the engineering schematics and wire harness drawings. Just prior to installation of the wrist roll drive, the slip ring was assembled and wired into the drive. The slip-ring provides the continuous roll capability while providing power to the end effector. The end effector was then installed.

The next operation was to set the arm in its nominal position and null the resolver in each drive joint. Then each drive was operated through the specified angular travel and the limit switches were set at the position extremes.

As the arm was assembled the counterbalances were installed at the three pitch drives. Just prior to final acceptance testing of the arm, the counterbalance was adjusted for nominal operations.

4.0 Hardware Testing

4.0 HARDWARE TESTING

4.1 General - The testing of the Proto-Flight Manipulator Arm was conducted in three phases--1) *design development tests*, 2) *qualification tests*, and 3) *acceptance tests*. These tests were performed in accordance with NASA-approved test procedures which were based on the requirements of the MSFC Specification 50M23186. The testing primarily demonstrated the functional performance of the drive joints under no load and full load, the operational capability of the drive joint design under thermal vacuum conditions, and the functional capabilities of the fully-assembled manipulator in a laboratory environment with the counterbalance installed. All performance requirements were met or were exceeded. Significantly, the maximum tip force of 45 Newtons or ten pounds was exceeded, providing the capability of 58 to 111 Newtons (13 to 25 pounds) depending on one or two drives in operation concurrently. The minimum operational rates which can provide a fine positional adjustment have been measured at 10 arc minutes/second. When this data is referenced to the wrist drives, position control is attainable to within 1.3 mm (0.05 inch) for each second of applied input voltage.

4.2 Design Development Tests - Design development tests were performed early in the program to evaluate the *thermal effects on the operational capability* of the drive joint design. With the gear backlash removed by gear adjustments, it was a concern that thermal contraction could increase tooth engagement and result in high starting torques. Thermal analysis had predicted a satisfactory condition and this was confirmed by test. The test unit was the wrist roll drive from the Martin Marietta 3.7-meter (12-foot) remote manipulator system. This unit was selected because its design was similar to the P-FMA drive design and the gear backlash was less than one arc minute. The tests were performed in an apparatus shown in Figure 17. A liquid nitrogen shroud encapsulated the drive and infrared lamps around the test unit regulated the specimen temperature. Torques were applied to the output end of the drive using a pulley and weights until motion was perceptible. Torques were factored to reflect input drive

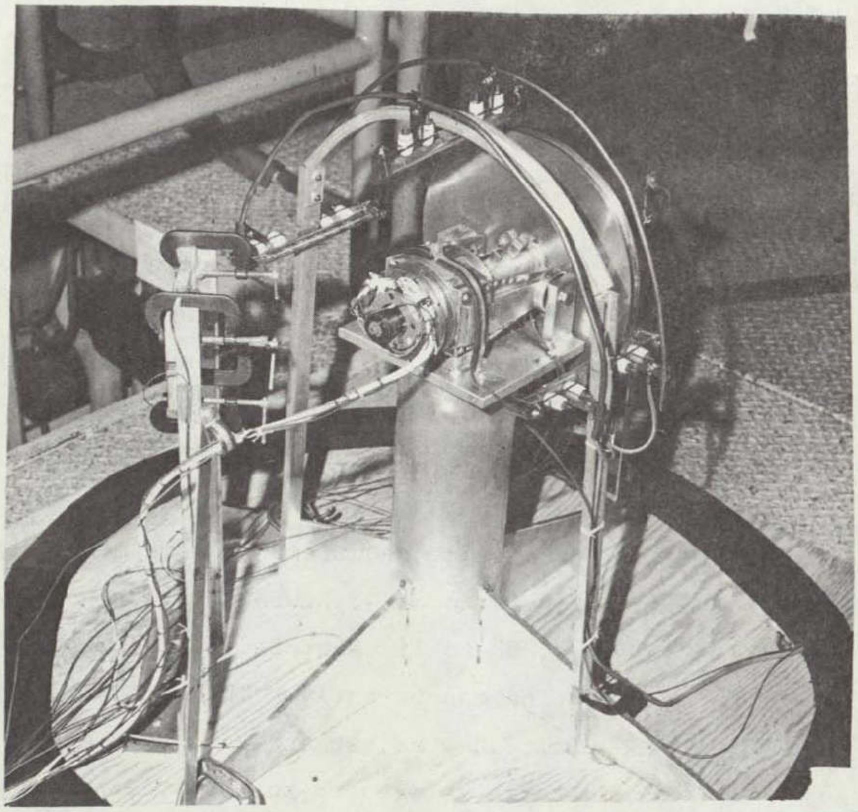

Figure 17 Design Development Thermal Test

torques. Figure 18 shows the effects of temperature on static friction (breakaway torque). The cold temperature effect was due to the increased lubricant viscosity. These tests concluded that cold temperature operations had only minimal effect on losses due to thermal contraction and that selection of lubricant must consider viscosity index.

Several *lubricants were tested* to evaluate the effects of temperature on viscosity. Various lubricants were applied to ball bearings and lightly pressed into retaining plates, as shown in Figure 19. The bearing torques were measured with a torque watch as the temperature was reduced. The results of these tests are shown in Table 7. It was concluded that a small heater in each drive would provide the assurance that the drive temperature could be maintained above -73°C (-100°F). Independent studies by NASA-MSFC identified a Braycote 3L38-RP grease that provided an improved viscosity index and also had low outgassing characteristics. This lubricant will be used for space environment operations, and the P-L Scientific L-11 (lithium-base grease with 2 percent molybdenum

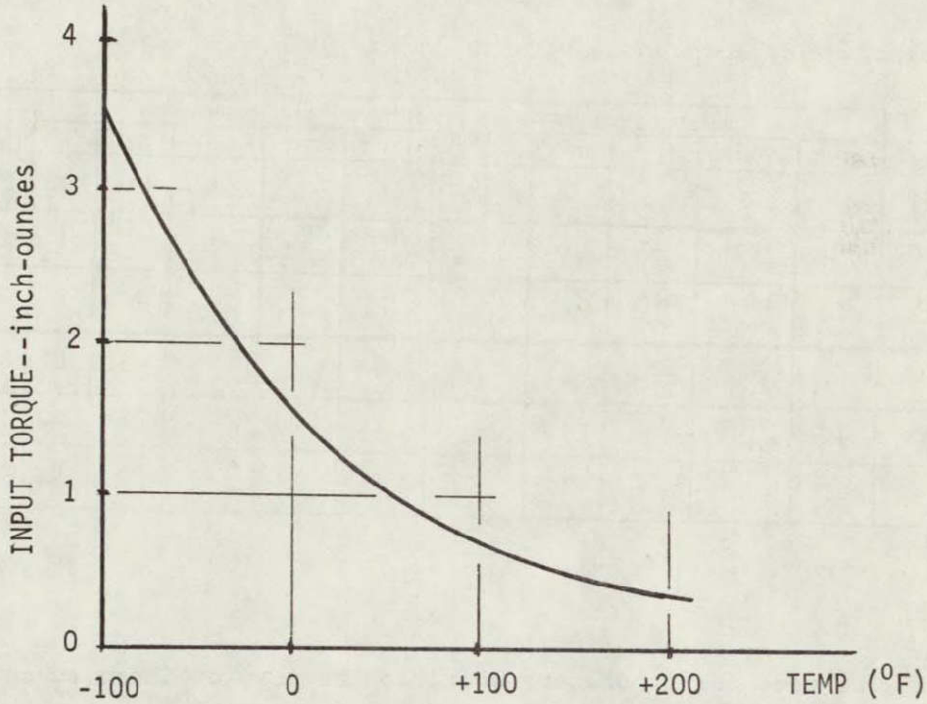

Figure 18 Static Friction/Temperature Curve

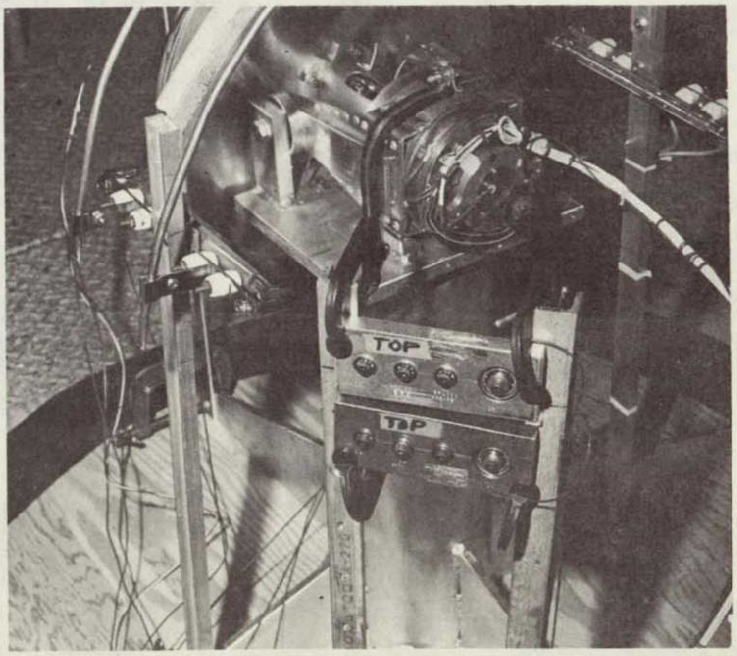

Figure 19 Temperature Tests of Lubricants

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Table 7 Temperature Effects on Lubricants

		Bearing Friction Torque (oz-inch) at Cold Temperatures										
	Lubricant	$-121^{0}F$	$-117^{0}F$	$-115^{0}F$	$-89^{0}F$	$-80^{0}F$	$-77^{0}F$	$-72^{0}F$	$-62^{0}F$	$-50^{0}F$	$-25^{0}F$	$0^{0}F$
Light Press in Aluminum Housing	Bearing Dry	-	0	0	-	0	0	-	0	0	0	0
	Brayco 631	-	Very High	Very High	-	Very High	Very High	-	20	3	1	0
	Brayco 813	-	Very High	Very High	-	Very High	Very High	-	Very High	12	1	0
Light Press in Steel Housing	Bearing Dry	0	0	-	0	-	0	0	-	0	0	0
	L-11 Grease	16	Very High	-	4	-	6	9	-	2	0	0
	L-11 Spray	3	0	-	1	-	0	0	-	0	0	0

disulfide) will be used for laboratory operation because of improved corrosion resistance properties.

A development test was conducted in vacuum to determine the extent of *motor rotor heating* with convective heat transfer eliminated. The wrist roll drive was installed in a vacuum chamber, as shown in Figure 20, and pumped to 1×10^{-4} torr. The motor was operated at stall with maximum rated input power for periods of 30 seconds. Maximum rotor temperature rises were approximately 30°C or 50°F. Subsequent thermal analyses concluded that the P-FMA drives would not experience a rotor temperature that exceeded its rated value of 155°C (310°F) when operating for 30 seconds at stall.

A component development test was performed on *electrical connectors* to verify the integrity of the units after exposure to the cold temperature extreme. Exposures - 77°C (-106°F) showed no structural or electrical degradation to the connector, inclusive of potting or wire insulation.

Tests were conducted to determine the best suited material for the *fail-safe brake grip surface*. The standard material--cork--was not compatible with the space environment. Twelve materials were tested to determine the most uniform coefficient of friction over the temperature range of -73°C (-100°F) to

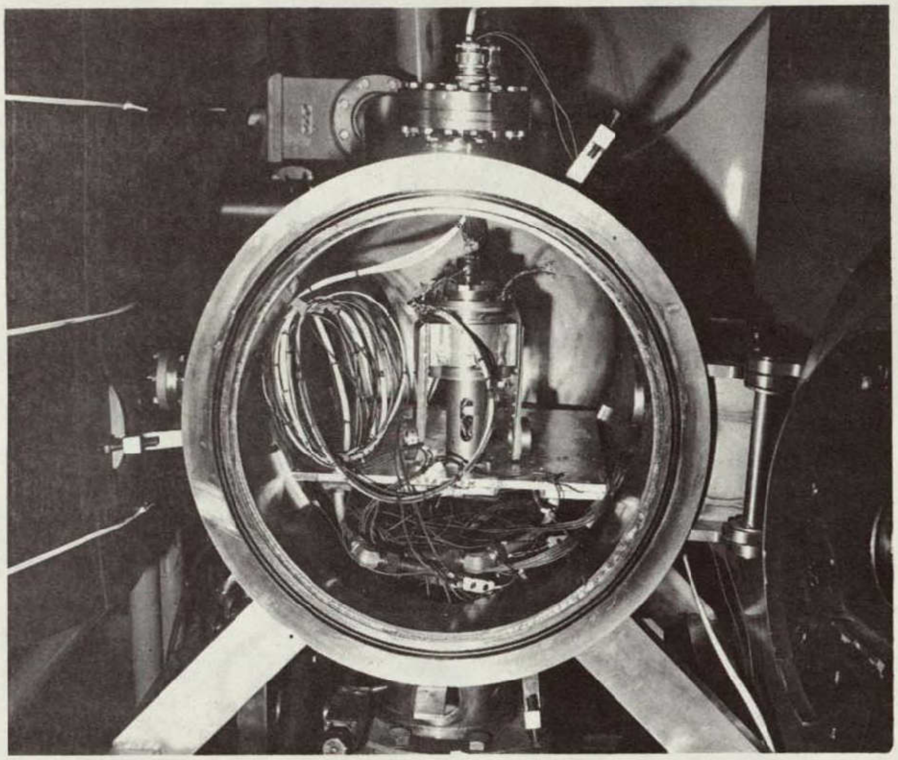


Figure 20 Motor Rotor Temperature Test

+93°C (+200°F). The Raybestos R860-6 showed the most consistent results and was selected as the brake material. Outgassing tests of the material were performed which showed a weight loss of less than 0.10% with volatile condensible materials of 0.05%.

4.3 Qualification Tests - The sole qualification test of the P-FMA was a thermal vacuum functional test of one drive joint. The test arrangements are shown in Figure 21. The wrist pitch drive was selected as the test specimen because it was most susceptible to temperature changes due to its low thermal mass, and it contained a temperature sensor as part of the design that would provide internal temperature monitoring capability. It had been modified to incorporate the Boeing compact brushes for the motor and tachometer, and had Braycote 3L38 grease as the lubricant for these tests. Tests were performed, as shown in Figure 22, at 1×10^{-6} torr with three thermal cycles from -73°C (-100°F) to +93°C (+200°F) with functionals performed at -73°C (-100°F), +27°C

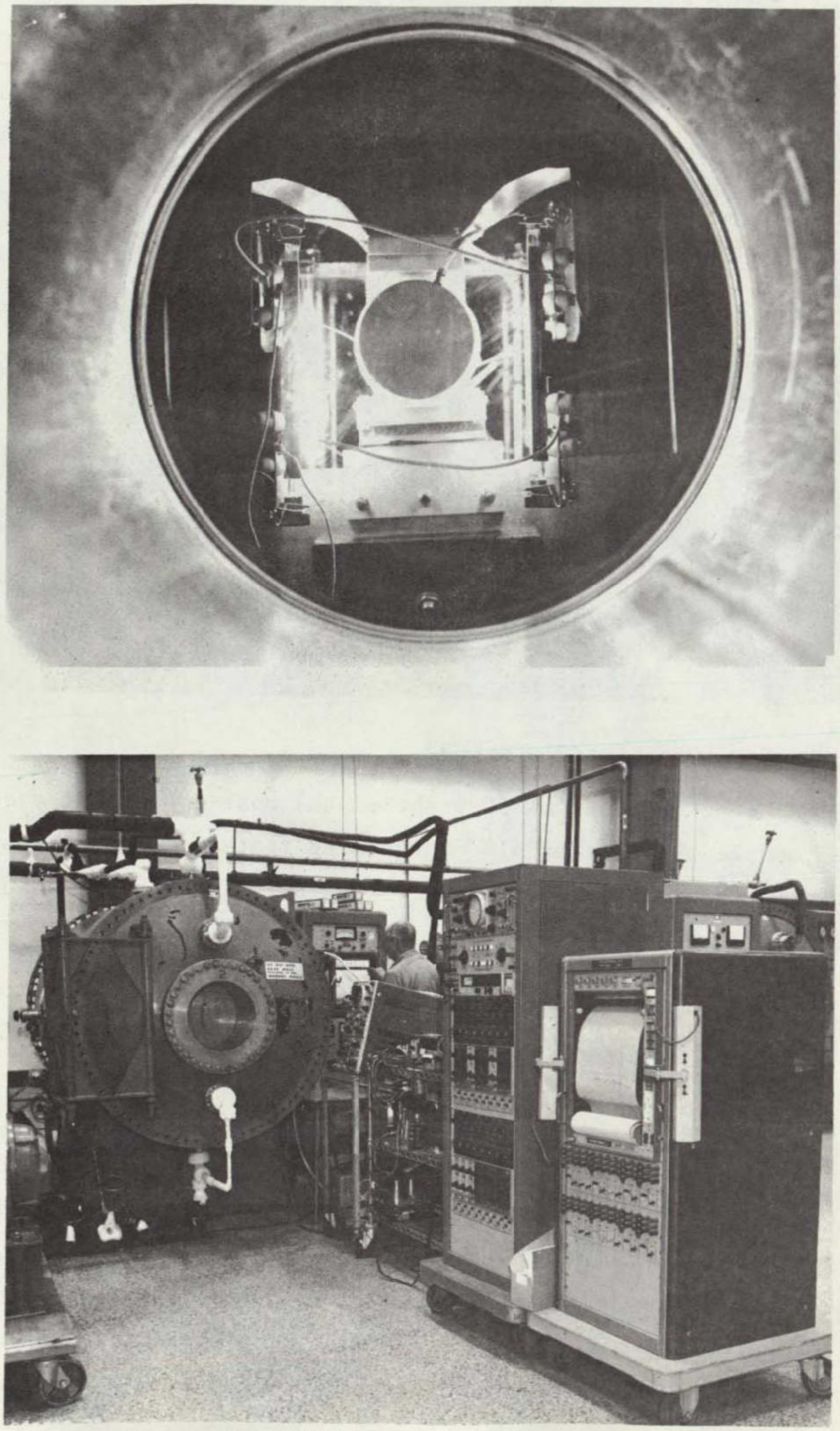


Figure 21 Thermal Vacuum Qualification Test

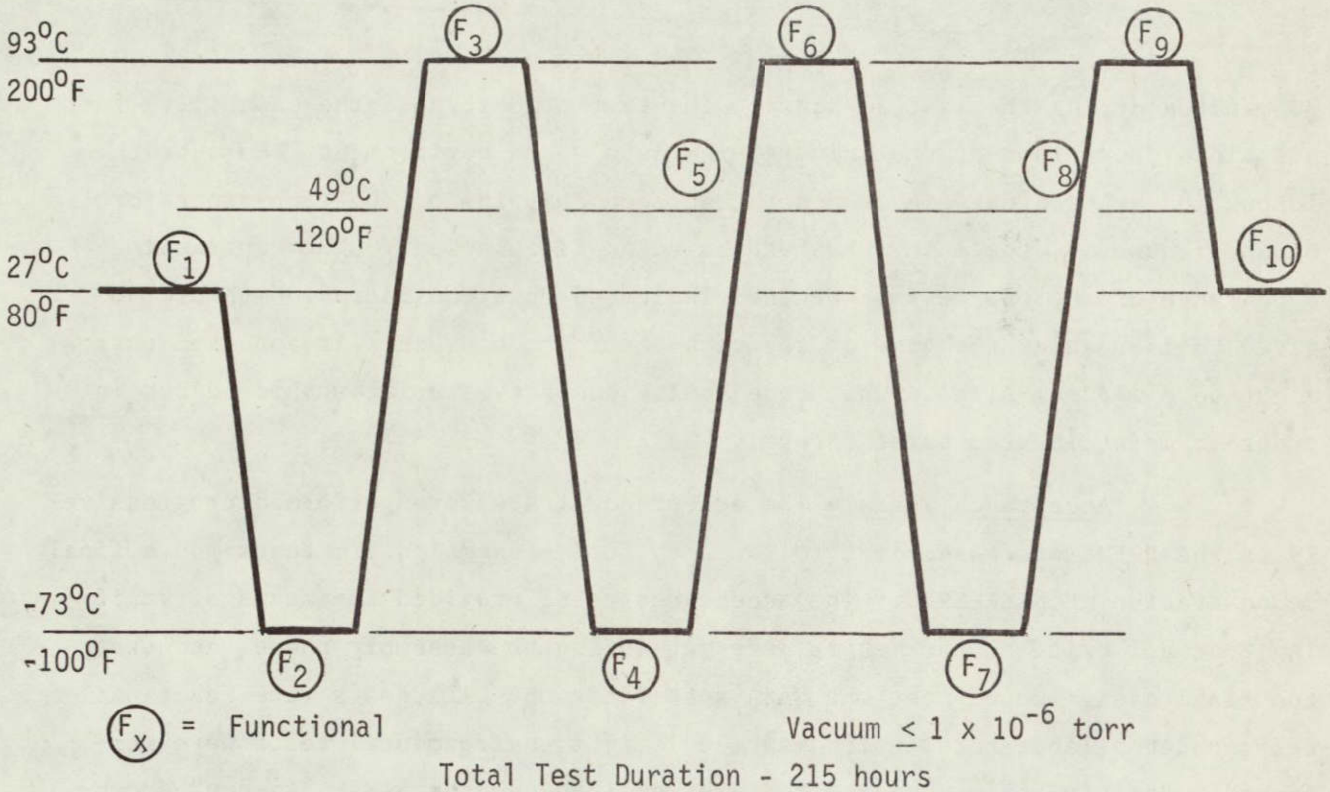


Figure 22 Thermal Cycles for Vacuum Qualification Test

(80°F), +49°C (120°F), and +93°C (200°F). A total of ten functional tests inclusive of no-load and full-load operations were performed. Additionally, an operational life test with rotational cycling was performed which accrued 93 hours of continuous operation without degradation of drive performance.

The performance capabilities of the drive were demonstrated in the space environment. It was noted that the drive had reduced performance at +93°C (200°F). At this temperature the drive operated at one-half the rotational rate at full torque. This condition had been predicted from motor performance analysis due to the I^2R loss resulting from rotor heating. However, our thermal analysis has predicted a maximum drive temperature of +27°C (81°F) at the external housing. Therefore, no performance degradation is anticipated during actual orbital operations.

The operational life test was performed for 93 hours at a vacuum of 1×10^{-7} torr and a temperature of 27°C (81°F). This test consisted of continuously operating the drive, changing the direction of rotation every five minutes during the first hour, every 15 minutes during the next 14 hours, and every

30 minutes during the last 78 hours. The test demonstrated the capability for sustained operations of the drive design in a space environment. Post-test inspections showed no effects other than some chipping of the tach-generator brushes; however, the motor brushes showed negligible wear. The contrasting appearance of the two sets of brushes indicated that consideration should be given to increasing the size of the tach-generator brushes. It appeared there might be a minimum size to which the Boeing compact material should be cut in order to maintain structural integrity.

4.4 Acceptance Tests - The acceptance tests were performed progressively as the P-FMA was assembled, followed by fully-assembled arm tests and a final demonstration at NASA-MSFC. The acceptance tests provided the means of verifying that all critical parameters were met during the assembly phases and that the final design would meet the NASA specification. All tests were functional tests under a laboratory environment; no flight environmental tests were performed. However, this subject is discussed in paragraph 5.2. "As-run" acceptance test procedures and data are on file at NASA-MSFC and Martin Marietta.

4.4.1 Drive Joint Tests - As the drives progressed through the assembly phases, they were tested for gear backlash, static friction, electrical continuity and resistance, insulation resistance, component performance, and drive joint performance. The following paragraphs briefly describe these tests.

a. The *gear backlash tests* were performed after installation of the gears and bearings into the drive housing. At the completion of the adjustment of the second gear mesh, gear backlash was verified to be less than one arc minute in all primary drives.

b. The *static friction tests* were performed immediately after the backlash tests. A torque was measured at the input shaft to determine the value to overcome friction and the torque variance throughout each drive, as an indication of concentricity and uniform gear mesh. Static friction torques of 0.24 - 0.32 Newton-centimeters (1/3 to 1/2 inch-ounce) were consistent on all primary drives.

c. The *electrical tests* were performed after installation of all components and internal wiring. Breakout boxes which interface with the drive joint power and instrumentation connectors were used for these tests. Continuity and resistances were verified; a 100-volt Megger test was performed to verify insulation integrity.

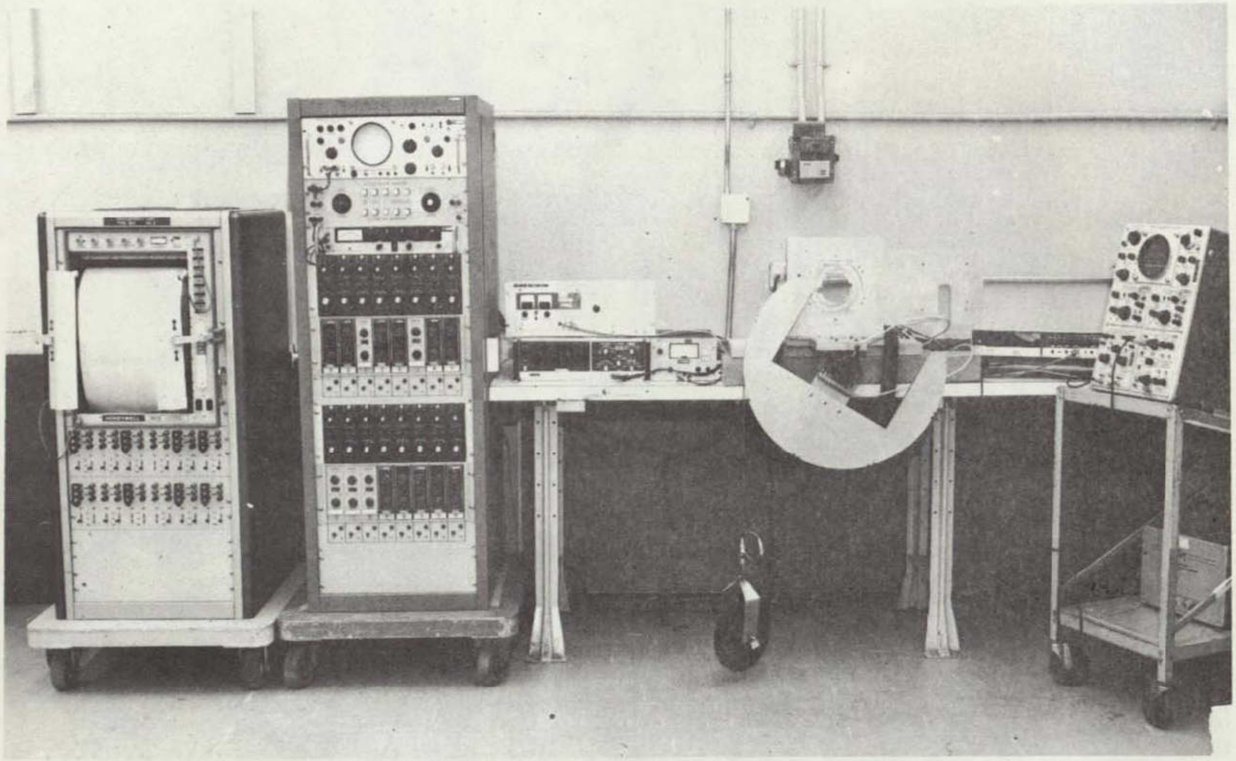
d. The *component performance tests* verify that all components meet functional requirements prior to final assembly of the manipulator arm. Most significant of these tests are the motor torque-speed relationship, tach-generator output, resolver performance, and fail-safe brake holding and slip torques. Vendor test data for these components have been supplied to NASA.

e. The *drive joint performance tests* verify the final performance of each drive. These tests were performed at no load and full load to verify torque and speed capabilities. Input power was monitored for each drive condition. A summary of these test results is presented in Table 8. Figure 23 illustrates a typical load test on

Table 8 Drive Joint Performance Data

Drive	Applied Torque (ft-lbs)	No-Load Velocity			Full-Load Velocity		
		volts	amps	rad/sec	volts	amps	rad/sec
Shoulder Yaw	90	11.0	0.3	0.20	29.9	3.5	0.20
Shoulder Pitch	90	11.3	0.2	0.21	29.8	3.3	0.21
Shoulder Roll	7	6.3	0.2	0.24	24.0	2.5	0.20
Elbow Pitch	50	19.0	0.2	0.39	30.0	2.3	0.24
Wrist Pitch	15	8.0	0.1	0.23	28.0	1.4	0.23
Wrist Yaw	15	8.0	0.15	0.23	28.0	1.4	0.23
Wrist Roll	15	8.0	0.1	0.22	24.0	1.0	0.23

the wrist pitch drive. During these tests the tach-generator output was checked against a stop watch to verify rotational rate. The resolver output was checked by measuring the actual drive rotation, using an inclinometer, for known rotations of the resolver. These tests are shown in Figure 24, where the resolver positions



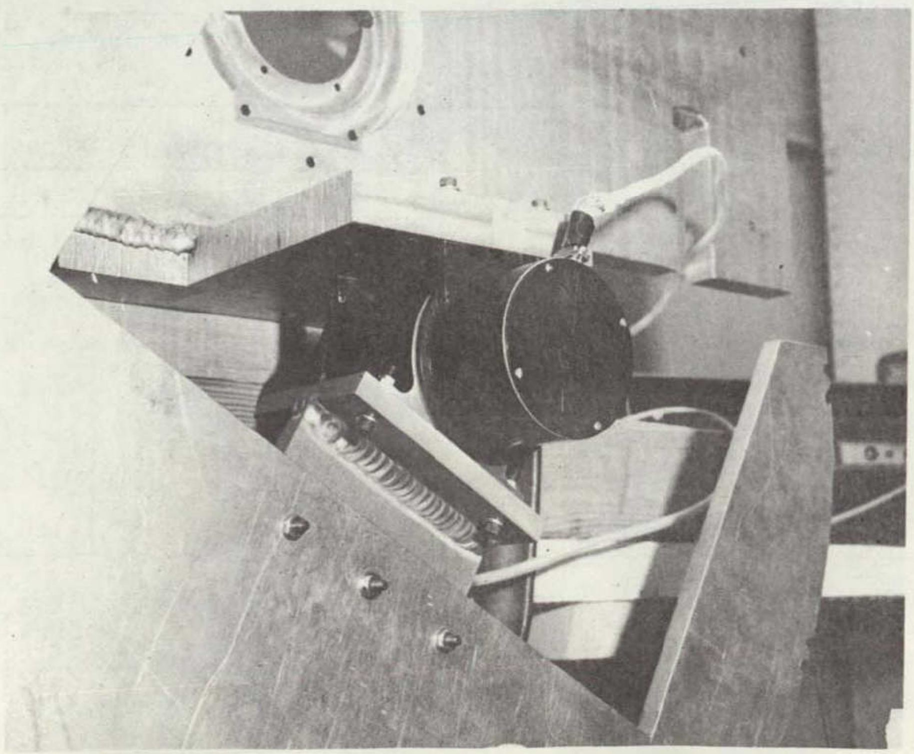


Figure 23 Drive Joint Load Tests

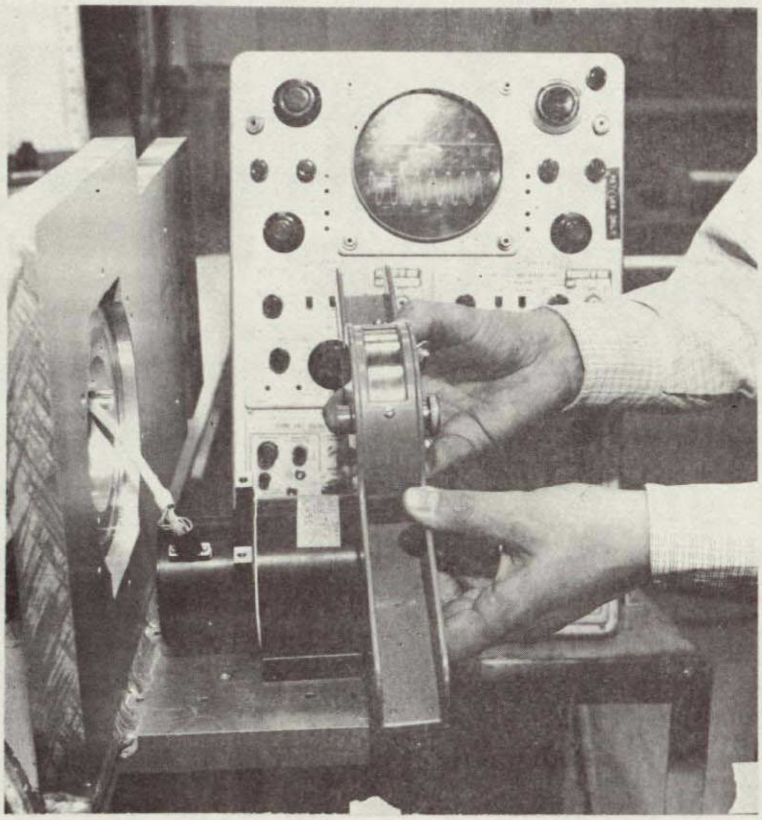
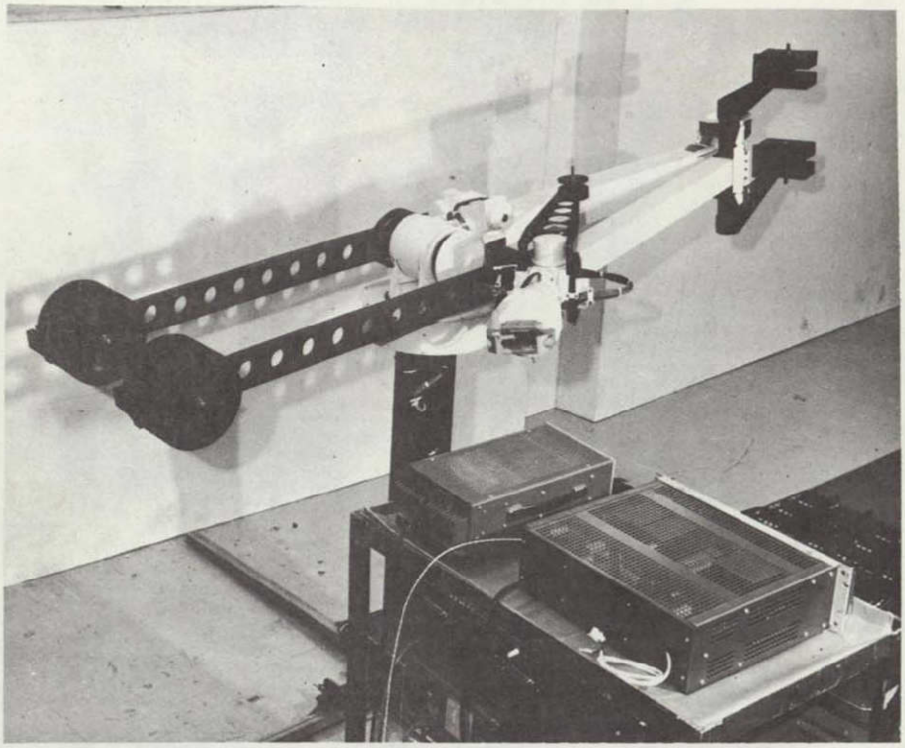


Figure 24 Resolver Position Tests

are indicated on the oscilloscope and are verified by digital voltmeter outputs. Position repeatability was verified to within 2 arc minutes for 360 degrees of drive rotation. During the drive joint performance tests the fail-safe brakes, heaters, temperature sensors, and limit switches were also verified to assure they were functional.

4.4.2 Assembled Manipulator Arm Tests - These tests were performed to demonstrate the fully assembled arm capabilities of dexterity, maximum reach, stowage configuration, angular travel of each degree of freedom, maximum tip force, and end effector performance. These tests were performed with the counterbalance installed on the arm in order to permit the drives to perform useful work. Figure 25 shows several of the manipulator arm configurations during these tests. These tests are described in the following paragraphs.

a. The P-FMA drives were powered to demonstrate the *dexterity* of the arm to have the end effector reach the shoulder drives. At *maximum*



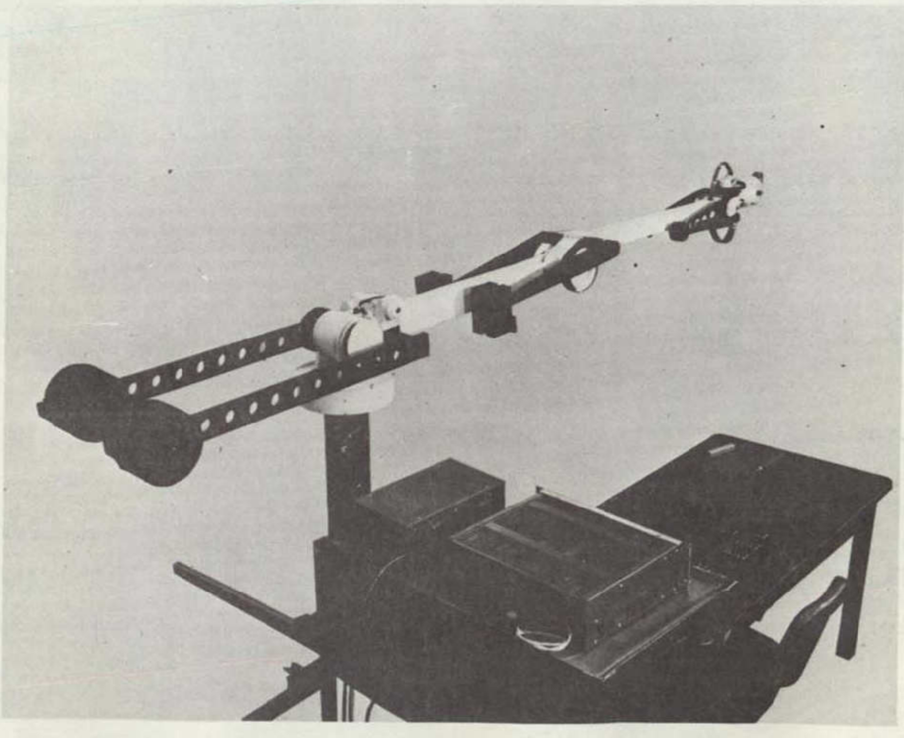


Figure 25 Manipulator Positions

reach, measurements were taken to verify a 3-meter (9.7-feet) reach from shoulder pitch to end effector jaw. The unit was powered into a *stowed configuration*, although the counterbalance (nonflight hardware) did cause some minor interferences. Stowage envelope dimensions were verified to be in accordance with the Interface Control Document (Appendix B).

b. The *angular travel* capability of each drive joint was verified and the limit switches were set to provide an indication of these travel limits. THE SWITCHES AND THE FAIL-SAFE BRAKES should be integrated into the control electronics to interrupt motor power and engage the brake when travel limits are reached. Angular travel limits are defined in the Interface Control Document (Appendix B).

c. The *maximum tip forces*, as applied in each direction along each of the three orthogonal axes, were demonstrated at 58-67 Newtons (13-15 pounds). This capability can be increased to at least 111 Newtons (25 pounds) when articulated motion is provided to the shoulder and elbow drives concurrently.

d. The *end effector performance* tests demonstrated the opening/closing rate and grip force. When integrated with the controls to vary supply voltage and current limiting, the opening/closing rate can be controlled to 2.5-38 mm/second (0.1-1.5 inches/second) and grip forces up to 400 Newtons (90 pounds).

4.4.3 P-FMA Demonstration - The P-FMA was delivered to NASA-MSFC where it was reassembled, counterbalanced, and demonstrated for NASA personnel. The manipulator was driven by analog voltage inputs directly from standard laboratory power supplies, through breakout boxes interfacing with the P-FMA base connectors, to the individual drive joints. The resolvers were energized by single phase, 400 Hertz, 26V AC supply voltage. The drives were operated one at a time while the tach-generator output, demonstrating the drive rate, was displayed on a digital voltmeter. The sine-cosine resolver output, demonstrating the drive position, was displayed on an oscilloscope. All electrical circuits were verified; however the room size prevented full travel in all degrees of freedom. All drives were demonstrated for torque capability, smoothness of operation, and backdriveability. Minimum rate demonstrations showed the low starting voltages required and minimum movement capability. The drives can be operated at 10 percent of rated voltage, resulting in manipulator motions that are not perceptible to the eye. A summary of the minimum movement capabilities are presented in Table 9.

Table 9 Minimum Movement Capabilities

Drive Joint	Minimum Input Voltage (volts)	Minimum Output Rate (min/sec)	Rate of Motion at End Effector (inches/sec)
Shoulder Yaw	2.3	5.0	0.17
Shoulder Pitch	2.0	4.2	0.14
Shoulder Roll	Indexing Only	N/A	N/A
Elbow Pitch	1.6	8.9	0.18
Wrist Pitch	1.7	10.7	0.06
Wrist Yaw	1.5	10.7	0.05
Wrist Roll	1.8	14.0	Rotational

NASA-MSFC is presently developing the electronic controls to enable the arm to be operated remotely in a rate-control mode from a pair of hand controllers. A closed-circuit television system will provide visual feedback. It is anticipated that the P-FMA with integrated controls will eventually fly as a teleoperator experiment on an early Shuttle Orbiter flight.

5.0 Conclusions and Recommendations

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions - This contract demonstrated that Martin Marietta in conjunction with NASA-MSFC had the technical capability to produce a general purpose manipulator that is operable in earth orbit. This arm is capable of performing useful work, as evidenced by testing that has demonstrated 111-Newton (25-pound) tip forces and end effector torques of 22 Newton-meters (16 foot-pounds). The precision of the individual drive joints has provided minimum rates that show smoothness of operation while motion is not perceptible to the eye. Maximum rates--both at full load and no load--can be controlled to 0.2 radians per second (11.5 degrees/second), correlating to tip speeds of 0.5 meter/second (1.8 feet/second). The backdrive capability permits the arm to absorb external forces without damage to the manipulator and also is useful in correcting misalignment problems during operation.

The minimum motion capability was accomplished by using precision gearing, accurate gear shaft alignment with precision bearings, and the performance qualities of a pancake torque motor. This minimum motion feature, when integrated with a properly designed control system, will offer positioning capability of 1.3 mm (0.05 inch) at the end effector. Position accuracies for this type mechanism may be improved, but such requirements should be investigated first. It has been our experience that other position errors such as mounting tolerance, target locations for the end effector, relative position between the free-flyer and the objective spacecraft, become very significant relative to the manipulator end effector positioning. In the case of general purpose operations, the present positioning capability of the manipulator is adequate. In the case of a dedicated servicing-type manipulator with a position control loop where position calibrations can minimize these extraneous position errors, it appears beneficial to use optical encoders instead of resolvers *at the shoulder drives*, providing improved position readout capability. However, the placement of encoders at other drives creates excessive design problems due to the large increase in the number of wires required in the wire harness, as well as the size and weight of the encoders. Due to the large thermal mass at the shoulder, a heater at this location would provide a uniform thermal environment to the encoders, even at the lowest anticipated orbital temperatures.

The design of the drive joints, similar for all torques from 20 Newton-meters (15 foot-pounds) to 122 Newton-meters (90 foot-pounds), can be extrapolated to significantly greater ratings. This was demonstrated by an in-house funded activity which produced a 1,625 Newton-meter (1,200 foot-pound) drive. A continuing effort to seek manipulator improvements has yielded the results that new samarium-cobalt torque motors of the sizes used in the Proto-Flight Manipulator Arm can provide a 30 to 50 percent increase in output torque. Of course, motor replacement must be preceded by further structural analysis. Where exceptionally long life is restricted by motor brush life, brushless direct current motors are also available. A Martin Marietta IRAD Task 45-D is in process to continue to study other drive improvements.

The development of the two adjustable gears within the three-stage, dual-mesh gear train has demonstrated an effective method of minimizing gear backlash, which is usually a major contribution to position error. The effectiveness was also demonstrated over the temperature extremes from -73°C (-100°F) to +93°C (+200°F).

The analytical techniques used in the design of the manipulator arm were shown to be correct and accurate. As a result, all specified performance requirements were met or exceeded.

The effectiveness of the programmatics used in this contract was demonstrated by the efficient production of the P-FMA for 100 manmonths of effort and in a period of performance of 21 months.

5.2 Recommendations - In order to make use of the manipulator produced under this contract, it is necessary to provide the control laws and the rate control servo-loops to give the arm articulated motion capability. It is strongly recommended this effort receive a NASA priority if the P-FMA is to be demonstrated in space in the early 1980's. In May 1976, a program statement of work was submitted to NASA for consideration. Using the same type cost-effective programmatics and the same design and test philosophy used on the P-FMA contract, a P-FMA rate control package will require 18 months to design, build, test, and deliver. This effort makes maximum use of the experience developed in performing a similar task on the manipulator, previously developed with internal Martin Marietta funding. Only when the controls have been integrated can the full utility of the Proto-Flight Manipulator Arm be demonstrated.

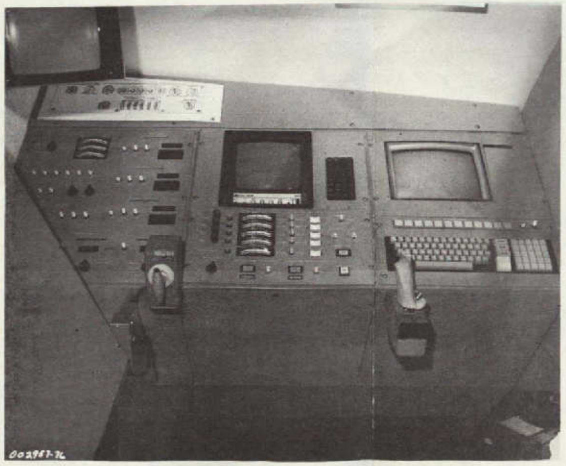
In order to prepare the P-FMA for an operational demonstration in low earth orbit within the Shuttle cargo bay, as illustrated in Figure 26, Martin Marietta strongly recommends the performance of a refurbishment of the P-FMA after the teleoperator controls have been integrated with the manipulator. The following activities constitute the minimum extent of that refurbishment. Other items may be required based on Shuttle integration requirements.

a. Electromagnetic Compatibility (EMC) Testing - The P-FMA is likely to be operated from a remote station through an RF link. The manipulator should be tested to determine the radiated and conducted emissions generated by the electrical components. This test will serve as a baseline for making design changes such as noise filters on the motors, additional shielding of conductors, and the use of shielded connectors.

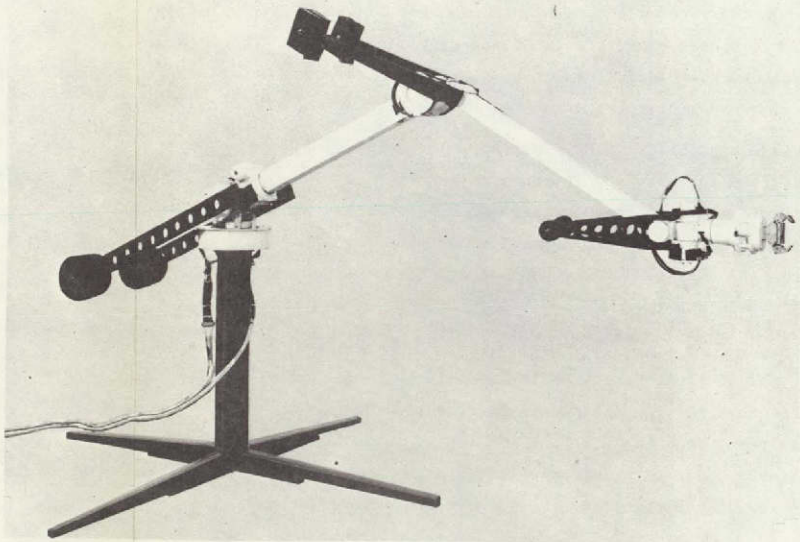
b. A preliminary flight-level vibration test should be conducted to verify the structural design and mechanical and electrical workmanship. This test, together with the EMC test, should be conducted *before* refurbishment in order to verify system compatibility and still provide the appropriate time to make corrective actions, if required.

c. The P-FMA must be refurbished prior to flight in order to remove the lithium-base grease and replace it with the Braycote lubricant. This requires a complete disassembly of the drive joints. This will also provide the opportunity to perform various inspections

(a) MMC Payload Specialist Station Operational Mockup



(b) Manipulator Control Station



(c) Proto-Flight Manipulator Arm

Figure 26 Flight Demonstration Elements

FOLDOUT FRAME

FOLDOUT FRAME 2

ORIGINAL PAGE IS OF POOR QUALITY

of the drive components after a significant amount of operating time. During this disassembly the internal wiring will be improved to replace the numerous microconnectors with lap-solder and sleeved connections. Single shielded conductors will be provided throughout the drives and the flat conductor cables used locally around the torque motors will be replaced by printed circuits with a shield plane. Noise filters, designed from the data obtained from the EMC tests, will be installed. Consideration should be given to revising the external wire harnesses by eliminating the existing service loops and replacing them with Poly-Twist housings at each drive. After electrical tests have been performed, all electrical connectors will be potted.

d. Further considerations should be given to the tachometer brush chipping that occurred during thermal vacuum operational life tests (see paragraph 4.3). It is recommended that the tachometer commutators be made slightly longer to enable the size of the Boeing compact brushes to increase. It is felt the size increase would reduce the tendency for the brushes to chip.

e. Flight acceptance testing should be conducted prior to final delivery to NASA. Functional acceptance tests similar to those conducted for the present effort would be performed prior to and after completion of the environmental acceptance tests. The environmental acceptance tests should include a repeat of the EMC and flight-level vibration tests. Other tests to be considered would be a thermal vacuum test of all drives and a mechanical shock test using a mass simulator to verify the structural interfaces under crash loads.

f. Prelaunch verifications should be conducted to replace the silver-graphite brushes with the Boeing compact brushes, verify operational performance, install the manipulator in the Orbiter cargo bay, and verify structural and electrical interfaces.

As part of a captive experiment aboard the Shuttle we recommend that a task panel, representative of the numerous general purpose operations, be designed and built with the standards that would make it flightworthy. Additionally, other end effector jaw configurations may be considered that would be interchanged by remote operations.

Although this section of recommendations may appear lengthy, Martin Marietta has demonstrated a cost-effective program approach during the development of the P-FMA. This same approach would be used in the performance of these recommended actions, applying the experience developed from flight hardware programs on Viking, Skylab, Apollo, and Gemini.

Appendix A

APPENDIX A

CONTRACT END ITEM SPECIFICATION

FOR THE

PROTO-FLIGHT MANIPULATOR ARM (P-FMA)

Document No. CEI-PFM-00000

Dated 28 February 1977

Contract NAS8-31487

Martin Marietta Corporation
Denver Division
P.O. Box 179
Denver, Colorado 80201

1.0 SCOPE

This specification establishes the configuration, performance, and acceptance requirements for the Proto-Flight Manipulator Arm (P-FMA), Part No. 849PFM00000-009 and -010. This Contract End Item (CEI) is intended for use in the Shuttle Transportation System (STS) on such vehicles as a remotely controlled Free-Flying Teleoperator type spacecraft. Prior to this application, the P-FMA shall be refurbished from its ground-based operational configuration, and shall fly as a Shuttle payload experiment to demonstrate its flight-worthiness.

2.0 APPLICABLE DOCUMENTS

The following documents form a part of this spe tent specified herein. In the event of conflict bet and detailed content of this specification, the latt

2.1 Military Documents

Number	Title	Ref. Para. Herein
MIL-STD-130	Identification Marking of U.S. Military Property	3.2.2.3
MS24123	Plate, Identification	3.2.2.3
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment and Facilities	3.2.2.5
MIL-W-6858	Welding, Resistance, Spot and Seam	3.2.2.2
MIL-W-8611	Welding, Metal Arc and Gas, Steels, and Corrosion and Heat Resistant Alloys; Process for	3.2.2.2
MIL-W-8604	Welding of Aluminum Alloys; Process for	3.2.2.2

2.2 NASA Documents

50M23186	Equipment Specifications for Manipulator Assembly of Remotely-Operated System	3.1
MSFC-STD-512	Standard Man/System Design Criteria for Manned Orbiting Payloads	3.2.2.5
NHB 5300.4(1C)	Inspection System Provisions Aeronautical and Space Systems Materials, Parts, Components, and Services	4.0
50M02442	ATM Material Control for Contamination due to Outgassing	3.2.2.1
SE-020-006-2H	Guidelines for Performing Failure Modes and Effects Analysis on the Solid Rocket Booster	3.3.1

2.3 Mar[illegible]

849PFM00000	Proto-Flight Manipulator Arm Assembly	1.0,3.2.1
ICD-PFM-00000	Interface Control Document for the Proto-Flight Manipulator Arm (P-FMA)	3.1.1, 3.1.4
RES 3157500	P-FMA Counterbalance Installation	3.2.1

3.0 REQUIREMENTS

3.1 Performance

The Proto-Flight Manipulator Arm (P-FMA) has been designed to meet the performance requirements of NASA-MSFC Specification 50M23186 as part of Contract NAS8-31487. Those performance requirements to be verified prior to the acceptance of the P-FMA are specified in succeeding paragraphs of this section 3.1.

3.1.1 Stowage Envelope - The external envelope of the P-FMA shall be in accordance with the P-FMA Interface Document, ICD-PFM-00000. The envelope dimensions are 153 cm x 107 cm x 41 cm (60 inches x 42 inches x 16 inches), excluding the dimensions of the laboratory counterbalance system and any restrictions caused therefrom.

3.1.2 Maximum Reach - The P-FMA when fully extended shall have a length of at least 2.4 meters (8 feet), as measured between the shoulder pitch centerline and the wrist pitch centerline.

3.1.3 Weight - The P-FMA in its flight configuration shall not exceed 52 kilograms (115 pounds) in weight.

3.1.4 Operations - The following operational tests will be performed prior to acceptance of the P-FMA.

a. Drive Joint Travel - The drive joints shall be capable of the following rotational travel, as defined in ICD-PFM-00000.

1) Shoulder pitch--3.2 radians (180 deg);

2) Shoulder yaw--±3.5 radians (±200 deg);

3) Shoulder roll--±1.6 radians (±90 deg);

4) Elbow pitch--+3.0 radians (+173 deg);
-1.7 radians (-100 deg);

5) Wrist pitch--±1.6 radians (±90 deg);

6) Wrist yaw--±1.6 radians (±90 deg);

7) Wrist roll--Continuous rotation.

b. Velocities - The drive joints shall be capable of the following no-load and full-load rotational speed:

1) Elbow pitch--0.40 radians/second (23 deg/sec);

2) All other drives--0.20 radians/second (11.5 deg/sec).

c. Applied Torques - The drive joints shall be capable of developing the following torques at rated velocity:

1) Shoulder yaw--123 Newton-meters (90 foot-lbs);

2) Shoulder pitch--123 Newton-meters (90 foot-lbs);

3) Shoulder roll--9.5 Newton-meters (7 foot-lbs) (arm indexing only);

4) Elbow pitch--68 Newton-meters (50 foot-lbs);

5) Wrist pitch--20.5 Newton-meters (15 foot-lbs);

6) Wrist yaw--20.5 Newton-meters (15 foot-lbs);

7) Wrist roll--20.5 Newton-meters (15 foot-lbs).

d. End Effector - The parallel-jaw end effector shall be capable of the following controlled operations;

1) Grip distance --8.9 cm (3.5 inches);

2) Grip closing/opening rate--0-3.8 cm/sec (0-1.5 in./sec);

3) Grip force--44.5-397 Newtons (10-89 lbs);

4) Nonbackdriveable--223 Newtons (50 lbs).

e. Manipulator Tip Force - With the P-FMA fully extended, the arm with power applied shall be capable of exerting 44.5 Newtons (10 lbs) of force at the end effector in each direction along the three orthogonal axes of the arm.

f. Failsafe Brake - Each drive except the shoulder roll (nonbackdriveable) shall have a failsafe brake that will restrain the drive when power is removed from the system.

g. Counterbalance - With the failsafe brakes energized and no power applied to the drive motors, the P-FMA shall remain in static equilibrium with the counterbalance installed.

3.2 Product Configuration

3.2.1 Design Drawings - The configuration of the P-FMA shall be in accordance with MMC drawing 849PFM00000-009 and -010 and drawings and engineering data assembled thereunder. A counterbalance system in accordance with MMC drawing RES3157500 is provided for laboratory operation of this manipulator.

3.2.2 Standards of Manufacturing - The manufacturing of the P-FMA shall be in accordance with standards and processes specified on applicable MMC drawings and those specified below.

3.2.2.1 Materials - Materials, finishes, and coatings shall conform to NASA-MSFC specification 50M02442, as supplemented by the Materials List for Proto-Flight Manipulator Arm.

3.2.2.2 Welding - Welding in the P-FMA shall be in accordance with the following specifications:

a. Aluminum Fusion Welding - MIL-W-8604;

b. Resistance Welding - MIL-W-6858;

c. Steel Fusion Welding - MIL-W-8611.

3.2.2.3 Identification and Marking - The P-FMA shall be marked for identification in accordance with MIL-STD-130. The end item nameplate shall conform to MS24123, and shall include but not be limited to the item nomenclature, part number, and serial number.

3.2.2.4 Workmanship - The P-FMA shall be fabricated in a workmanlike manner in accordance with generally accepted industry practices. The end item, assemblies, plating, and welding shall be free of burrs and sharp edges that might cause injury to operating personnel.

3.2.2.5 Human Engineering - The P-FMA and the associated controls shall be in accordance with the design criteria of MIL-STD-1472 and MSFC-STD-512.

3.2.2.6 Cleaning - The P-FMA shall be cleaned in accordance with NASA standards for instrumentation (visually clean under normal white light).

3.2.3 General Description - The P-FMA shall be attached to a free-flying teleoperator spacecraft and be used as a general purpose arm to remove and replace modules on an orbiting satellite, after having firmly docked to that satellite. The P-FMA has seven (7) degrees of freedom plus the end effector operation. Six (6) of the drives (shoulder pitch and yaw, elbow pitch, and wrist pitch, yaw, and roll) are all of one typical design, but sized for specific torques. The seventh drive (shoulder roll) is only a position indexing drive.

3.2.3.1 Joint Drive Description - The six typical drives have a dual mesh, three-stage gear train of AGMA Class 12 gears. A direct-current pancake torque motor and a tach-generator (rate feedback transducer) are mounted on the input shaft. The failsafe brake is also mounted on an extension of the input shaft. The final gear stage has adjustable gears set at final assembly to remove the cumulative gear backlash from the gear train in each direction. The final gear mesh is two pinions and an internal gear that is rigidly attached to the outer housing of the drive. A brushless sine-cosine resolver (position feedback transducer) is driven by the output gear shaft through an anti-backlash gear. The drives have a limit switch to indicate the end of full travel and THESE SWITCHES SHOULD BE WIRED INTO THE MOTOR POWER CIRCUIT ALONG WITH THE FAILSAFE BRAKES when the control circuitry is designed for the P-FMA.

Each drive contains a small heater to prevent drive temperatures from reaching -73°C (-100°F) during normal orbital operations. The three (3) pitch drives (shoulder, elbow, and wrist) have a temperature sensor that will provide an indication of the drive temperatures along the length of the arm. Each drive is capable of operating for 30 seconds at rated torques without exceeding the maximum motor rotor temperatures of 155°C (310°F).

3.2.3.2 Shoulder Roll Drive Description - The shoulder roll drive is only for the purpose of position indexing of the P-FMA prior to articulated operations. It is a worm-drive with the direct-current pancake torque motor and the worm gear on the same shaft. A small worm gear located at the end of the shaft drives a sine-cosine resolver through an anti-backlash gear. The worm-wheel is rigidly mounted to the upper arm segment to provide the rotational capability. This drive contains a limit switch to indicate the rotational limits. Since the shoulder roll is a worm drive and is not backdriveable, it requires no failsafe brake.

3.2.3.3 End Effector - The end effector has a parallel-jaw operation that is driven from a direct-current pancake torque motor through a spiroid gear set. Control circuitry can be provided to regulate closing speed and grip force.

3.2.3.4 Arm Segments - Two (2) sets of arm segments are provided-- 1) One set to provide the 2.4 meter (8 foot) reach capability, and 2) one set to provide the 1.2 meter (4 foot) reach capability. The arm segments are square standard aluminum extrusions that have been chemically milled to reduce the weight of the segments.

3.2.3.5 Wire Harness - The P-FMA has two wire harnesses that extend the length of the arm. The power harness originates with a 37-pin base connector and contains the power leads for the motor, brake, and heater within each drive, as well as the case ground. The power harness is terminated at each drive with a 9-pin connector to interface with the power connector on the drive. The only exception is the wrist roll interface which is a 15-pin connector in order to accommodate the end effector motor.

The instrumentation harness originates with a 78-pin base connector and contains the leads for the resolver excitation and outputs, tachometer output, limit switch indications, temperature sensors (pitch drives only), and spare leads (for end effector only) for each drive. The harness is terminated at each drive with a 15-pin connector that interfaces with the instrumentation connector on each drive.

3.2.3.6 Maximum Power - The maximum power consumption of the P-FMA shall not exceed 500 watts. The supply voltage to be supplied to the P-FMA shall be controllable from 0-31 Vdc for all components except the position resolvers. This supply voltage shall be 26 VAC, 400 hertz.

3.2.3.7 Counterbalance - The counterbalance system is provided to permit laboratory operations of this flight-worthy manipulator. The counterbalance is disconnected (unbolted) from the three pitch axes in order to provide the space version of the P-FMA. Additional hardware is provided to counterbalance the 1.2 meter (4 foot) arm configuration. When lightweight payloads are being handled in the laboratory, the three counterbalance segments must be readjusted by the addition of compensating weights.

3.2.3.8 Other Considerations - P-FMA has been designed for flight usage and has been delivered with two (2) sets of brushes for each motor and tachometer. The drives have silver-graphite brushes installed for laboratory operations. During space environmental operations, all brushes must be replaced with the spare brush ring assemblies, having brushes made of Boeing compact 046-45.

The drives are presently lubricated with a lithium-base molybdenum disulfide (MoS_2) grease that will withstand high contact pressures and provides adequate corrosion resistance. During refurbishment of the P-FMA for space environmental operations, the existing lubricants must be removed and replaced with a Braycote 3L38 grease that has a flat viscosity index and low outgassing characteristics.

During the refurbishment for flight operations, the internal drive wiring shall be replaced to eliminate the numerous electrical connectors, improve the flat conductor wires, and increase wire shields to suppress electromagnetic interference.

3.3 Operational Capability

3.3.1 Useful Life - The P-FMA shall be designed to last for a useful lifetime of five (5) years and/or 1,000 hours of operation, as a design goal. Reliability analyses for wear characteristics and a Failure Modes and Effects Analysis shall be performed in accordance with NASA specification SE-020-006-2H.

3.3.2 Maintainability - The P-FMA shall be designed to provide accessibility, replaceability, and serviceability consistent with efficient servicing, testing, and maintenance practices. Components expected to require servicing shall be designed to be accessible. A minimum of special tools shall be required.

3.3.3 Operational Environments - In addition to operational capability in the earth ambient laboratory environment, the P-FMA shall be capable after refurbishment to operate in a low-earth orbital environment consistent with temperatures of $73^{\circ}C$ ($-100^{\circ}F$) to $93^{\circ}C$ ($+200^{\circ}F$) and vacuum of 1×10^{-7} mmHg.

4.0 QUALITY ASSURANCE

The quality assurance provisions specified herein constitute the requirements for acceptance of the P-FMA. These provisions are based on NASA Document NHB 5300.4 (1C) and the P-FMA Quality Assurance Plan generated therefrom.

4.1 In-Process Inspections

Visual inspections of the assembled contract end item and inspections as necessary during fabrication shall be performed to verify compliance with the applicable drawings and the configuration requirements of paragraph 3.2.

4.2 Tests and Verifications

The capabilities of the P-FMA shall be tested and verified to meet the requirements of paragraph 3.0. These tests shall be conducted in accordance with applicable test procedures, as prepared by MMC and approved by NASA-MSFC.

4.2.1 Acceptance Tests - These tests shall be performed by MMC at the contractor's facility under local ambient conditions in order to verify the performance requirements of paragraph 3.1 and the configuration requirements of paragraph 3.2. The basic elements of these tests are-- 1) joint drive functional tests, 2) component performance tests, and 3) assembled arm tests.

4.2.2 Qualification Tests - These tests will be performed by MMC at the contractor's facility to verify the performance of one (1) drive joint under the orbital environment specified in paragraph 3.3.3. This test will also demonstrate the capabilities of paragraph 3.3.1, by a continuous operation in the orbital environment for a period of 94 hours.

4.2.3 Demonstration Test - The P-FMA shall be demonstrated by MMC at NASA-MSFC in order to show operational performance. Operations to be demonstrated are: 1) Operation of each drive joint, 2) Movements from the stowed position to the maximum reach position and back to the stowed position, 3) Manipulator tip force capability, and 4) End effector operations.

4.3 Post-Test Inspection

The P-FMA shall be visually inspected after the acceptance tests to inspect final finishes and cleanliness and to assure that no damage has occurred as the result of testing. Test data will be reviewed and a quality assurance stamp affixed to indicate this review.

5.0 PREPARATION FOR DELIVERY

5.1 Packaging - The P-FMA shall be partially disassembled and packaged in the most economical method acceptable to the common carrier, which will assure safe and proper delivery to destination. Packaging shall be labeled with a warning that a delicate instrument is involved. The unit shall be shipped to NASA-MSFC, Huntsville, Alabama.

5.2 Shipping Document Review

Prior to shipment, the Acceptance Data Package shall be inspected to verify its contents of:

a. Shipping Document (DD Form 250)

b. Top Assembly Drawing

c. Electrical Schematic

d. Interface Control Document

e. "As-Run" Acceptance Test Procedure with data

f. Copies of all DAR's, Waivers, and MRB Actions

Appendix B

APPENDIX B

INTERFACE CONTROL DOCUMENT

FOR

THE PROTO-FLIGHT MANIPULATOR ARM (P-FMA)

Document No. ICD-PFM-00000

1 November 1975

Revised 21 January 1976
Revised May 1976
Revised March 1977

Approved:

William R. Britton
Program Manager

Approved:

John L. Burch
National Aeronautics and Space Administration
Marshall Space Flight Center

MARTIN MARIETTA CORPORATION
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FOREWORD

This document is prepared and submitted in accordance with the requirements of paragraphs II.A.5, 6, and 7 of Exhibit A of Contract NAS8-31487. It will be updated periodically during the period of performance of the contract.

CONTENTS

INTERFACE CONTROL DOCUMENT FOR THE PROTO-FLIGHT MANIPULATOR ARM (P-FMA)
Document No. ICD-PFM-00000
1 November 1975 Revised May 1976

1.0 SCOPE

This Interface Control Document (ICD) establishes the interfacing requirements between the Proto-Flight Manipulator Arm (P-FMA) and the Earth Orbiter Teleoperator Spacecraft (EOTS) or other interfacing spacecraft.

The scope of this document defines the mechanical, electrical, and thermal interfaces that are required to have proper performance of the manipulator arm, as specified in NASA-MSFC Specification No. 50M23186.

2.0 APPLICABLE DOCUMENTS

The following documents, of the issue shown, form a part of this ICD to the extent specified herein.

2.1 Specifications

a. NASA-MSFC

50M23186	Equipment Specifications for Manipulator Assembly of Remotely-Operated System, dated 12 December 1974.
50M02442	ATM Approved Materials, Revision W
NHB 5300.4(1C)	Inspection System Provisions for Aeronautical and Space System Materials, Parts, Components, and Services, dated July 1971

2.2 Drawings

a. MMA

849PFM00000

2.3 Other Documents

A. XXXXX (TBD)	"Operations, Maintenance, and Calibrations Manual - P-FMA"

3.0 REQUIREMENTS

3.1 Operations

The primary function of the manipulator arm is to remove and replace modules on an orbiting satellite within a distance of 5000 meters of a Shuttle Orbiter. The manipulator is baselined to be a general purpose space tool attached to the Earth Orbiter Teleoperator Spacecraft (EOTS) and is operated from the Shuttle Orbiter control station.

The Proto-Flight Manipulator Arm (P-FMA) is a precursor to the EOTS manipulator. The P-FMA is capable of operating to remove/replace modules in a low earth orbit environment, such as from within the Shuttle cargo bay. The P-FMA is capable of very limited earth-bound (one-g) operations unless a counterbalance is applied which significantly increases the arm utility.

3.2 Mechanical Interface

The manipulator arm has angular travel in each joint as shown in Figure 1. The manipulator arm is designed to mechanically attach to an interfacing structure such as an EOTS or a mounting fixture. The P-FMA mounting base geometry is shown in Figure 2. Holddown provisions must be provided on EOTS at the elbow pitch drive and at the wrist roll drive.

3.3 Electrical Interface

The electrical interface is accomplished by the mating to two (2) electrical connectors--(1) power connector for the motors, brakes, and heaters; and (2) instrumentation connector for resolvers, tachometers, switches, and temperature sensors. The electrical interface is described in Figure 3 (pin number identification table TBD).

3.3.1 Power Consumption - The maximum power consumption of the manipulator arm will not exceed 500 watts. The average power will not exceed 240 watts. (These values may be reduced as the result of acceptance testing and typical task simulations.)

3.3.2 Power Source - The manipulator arm shall be operable at its rated torques and velocities at a voltage level of 28 $\pm$ 4V DC, as supplied from the EOTS, or equivalent.

3.3.3 Position Resolver Supply Voltage - The seven (7) position resolvers will require 26V 400 Hz primary output, supplied by the EOTS or control electronics. The two primary input leads from a common source are parallel for all seven resolvers.

3.3.4 Heater Supply Voltage - The seven heaters may require continuous 28 ± 4V DC power from the control electronics during space operation. The DC leads are common for all heaters in parallel.

3.3.5 Brake Voltage - The six brakes will require 28 ± 4V DC from the control electronics applied simultaneous with joint operation. The plus DC lead is common for all brakes in parallel and is paralleled with the plus DC for the heaters.

3.3.6 Temperature Sensor - The three temperature sensors are designed for use as one leg of a four-leg instrumentation bridge network with a maximum of one milliwatt applied to the sensor. The sensor resistance is 150 ± 0.5 ohms at 0°C. The bridge ground lead is common for the three sensors in parallel.

3.3.7 Position Switches - The Six position switches are designed and wired to carry the positive supply voltage through the common terminal with a maximum current of 0.5 amperes for a resistance load or 0.25 amperes for an inductive load. The positive voltage lead is common to all switches in parallel.

3.3.8 Case Ground and Shielding - A common case ground lead to all joints terminates in a pin in the power harness connector. This lead is required if noise filters are used at the motors. All shields are open ended at the component end and carried out to a pin on both the power harness and instrumentation harness connectors.

3.4 Weight

The manipulator arm is designed to a minimum weight but shall not exceed 45.4 Kg (100 lbs). The weight distribution is presented in Table 1.

3.5 Stowage Volume

With the manipulator arm in its stowed configuration, the stowage configuration and dimensions are shown in Figure 4.

3.6 Thermal Interface

The manipulator arm temperatures have been analytically determined, using the TRASYS II computer program to establish the thermal environment and radiation interchange, and the MITAS II computer program which solves the temperature prediction equations. The manipulator arm was configured in the stowed mode as shown in Figure 5 and in the deployed mode as shown in Figure 6. All external surfaces had a solar absorptivity (α) of 0.2 and an infrared emissivity of 0.89. Since the arm is primarily aluminum, a specific heat of 0.2 BTU/lb-°F was assumed. The weight distribution is presented in Table 1.

The environments were chosen to represent extreme cold and hot conditions to be encountered by the EOTS spacecraft. The cold environment was generated for the stowed configuration with the EOTS in the earth shadow and tilted at 45 degrees to the orbit plane. The earth orbit was at 400 km, circular, and equatorial. The hot environment was generated for the deployed configuration with the EOTS continually in the sun and tilted at 45 degrees to the orbit plane. The earth orbit was at 400 km, circular, and polar.

The results of the thermal analysis are summarized in Table 2.

Table 2 Steady State Temperature Results

Case No.*	Temperatures (°F)				
	1	2	3	4	5
Shoulder Yaw	-84	-15	-129	-12	136
Shoulder Pitch	-95	-17	-124	-25	137
Shoulder Roll	-85	-73	-122	-102	95
Upper Arm	-67	-65	-114	-111	93
Elbow Pitch	-60	4.3	- 97	- 18	114
Lower Arm	-61	-59	-107	-105	105
Wrist Pitch	-97	-11	-132	- 18	125
Wrist Yaw	-83	-15	-119	- 14	139
Wrist Roll	-78	-15	-113	- 19	139

*Case 1 and Case 3 are the cold environments, stowed and deployed configurations respectively, and with no heaters activated.

Case 2 and Case 4 are the cold environment, stowed and deployed configurations respectively, and with the heaters activated.

Case 5 is the hot environment, deployed configuration with electrically powered components activated.

The analysis demonstrates that motor rotors (nonoperating) are controlled between -73°F and +139°F. The shoulder yaw drive, which interfaces with the EOTS structure, is controlled between -15°F and +136°F. The cold extreme could drop to -84°F, if the heaters were not activated.

3.7 Controls and Electronics

The manipulator arm and controls/electronic interfaces are defined in terms of the manipulator arm electrical and mechanical parameters. These values will provide the control and electronic designers all necessary information to accomplish the controls analysis and the drive electronics design.

The motor and joint gear train parameters are listed in Table 3, and tachometer generator in Table 4. The position resolver specifications are defined in Table 5. The resistance values for the brakes are shown in Table 6 and for heaters in Table 7. The calculated joint inertias for both the loaded and loaded cases are defined in Table 8 and Table 9. All values listed are as received from the respective suppliers at time of procurement.

Figure 7 is the block diagram for a rate servo-loop control system. This diagram with the above listed parameters and certain assumptions such as input signal and system compliance were used to design a rate loop servo system. This analysis proved that the arm hardware selected can be controlled and meet bandwidth and phase margins as specified.

3.8 Useful Life

The useful life of the manipulator arm shall include the period from final acceptance through shelf-life, prelaunch life, operating life, and until destruction of its identity. This total time shall be a minimum of five years.

3.8.1 Operating Life - The operating life of the manipulator arm shall be designed for 1000 working hours in free space without refurbishment. Operating life will start accumulating with the acceptance testing and qualification testing of the drive joint. Operating time records shall be maintained in the unit historical record.

3.8.2 Shelf Life - During long periods of storage, the manipulator arm shall be stored in its protective container, after having been placed in double air-tight bags which have been sealed and protected from exposure to high humidity. The unit shall be placed in an area whose environment is controlled such that the humidity remains below 60 percent relative humidity and the temperature remains between 50°F and 80°F.

4.0 INSTALLATION PROCEDURES

The instructions for installing and calibrating the manipulator arm on the EOTS are presented in MMC Document (TBD).

5.0 OTHER CONSIDERATIONS

5.1 Materials

All materials used in the manufacture of the manipulator arm shall be in accordance with ATM 50M02442 or exceptions as approved by NASA.

5.2 Quality Assurance Provisions

Since the manipulator arm has the capability of low earth orbital operations, the design, manufacture, and test of this unit are controlled by the quality assurance provisions of NHB 5300.4(1C).

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C-2

B-8

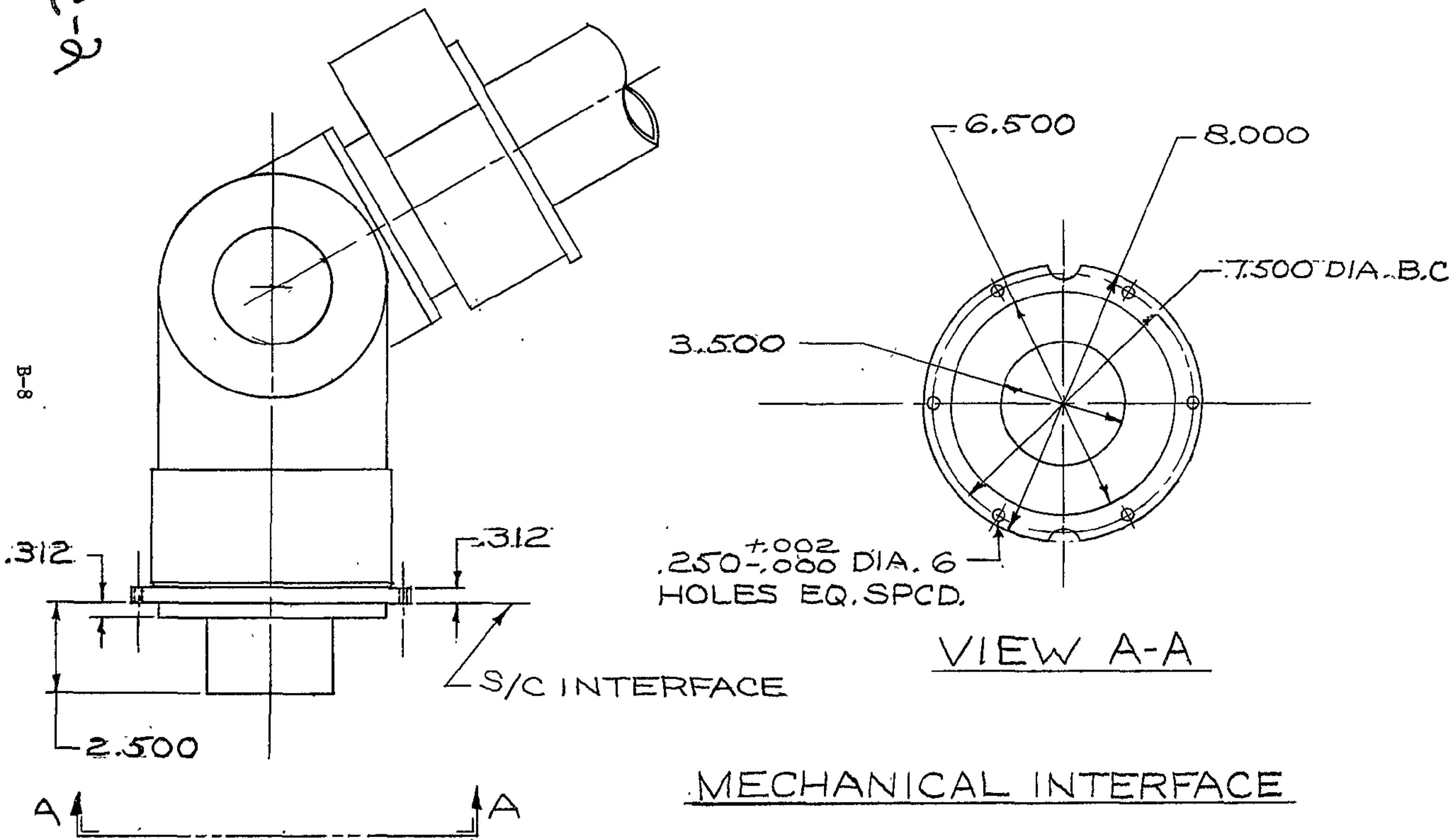


Figure 2 Mounting Interface to EOTS

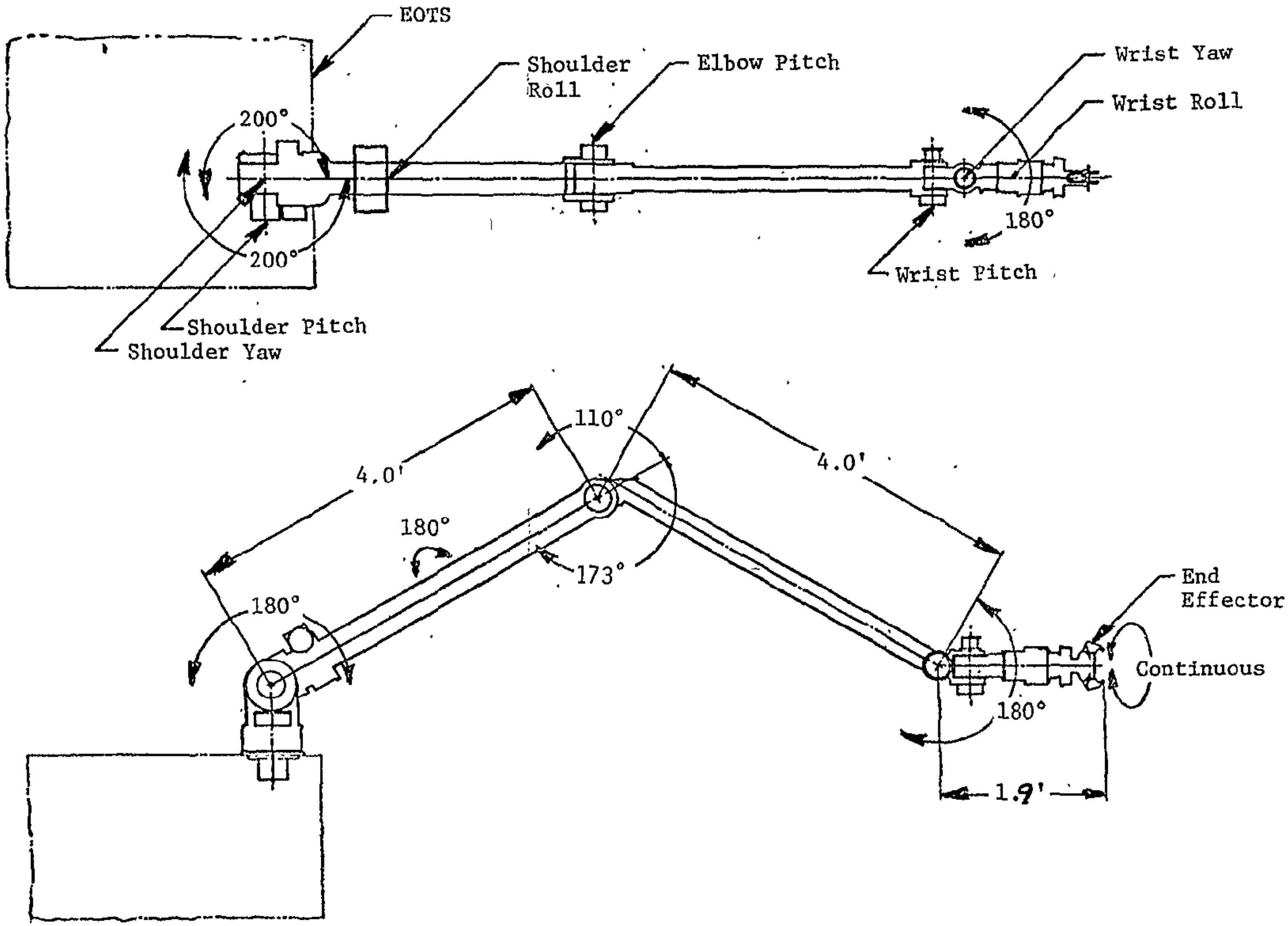


Figure 1 P-FMA Deployed Configuration

Added 6/8/76
Revised 02/18/77

Instrumentation Harness (DDMAM78P Connector on P-FMA)					
Pin No.	Identification	Pin No.	Identification	Pin No.	Identification
1	Shoulder Yaw Resolver S1	22	Shoulder Roll Resolver S3	44	Wrist Pitch Switch NO
2	Shoulder Yaw Resolver S3	23	Shoulder Roll Resolver S2	45	Wrist Pitch Switch NC
3	Shoulder Yaw Resolver S2	24	Shoulder Roll Resolver S4	46	Wrist Pitch Tach Generator +
4	Shoulder Yaw Resolver S4	25	Shoulder Roll Switch NO	47	Wrist Pitch Tach Generator -
5	Shoulder Yaw Switch NO	26	Shoulder Roll Switch NC	48	Wrist Pitch Temp. Sig
6	Shoulder Yaw Switch NC	27	Elbow Pitch Resolver S1	49	Wrist Yaw Resolver S1
7	Shoulder Yaw Tach Generator +	28	Elbow Pitch Resolver S3	50	Wrist Yaw Resolver S3
8	Shoulder Yaw Tach Generator -	29	Elbow Pitch Resolver S2	51	Wrist Yaw Resolver S2
9	Shoulder Pitch Resolver S1	30	Elbow Pitch Resolver S4	52	Wrist Yaw Resolver S4
10	Shoulder Pitch Resolver S3	31	Elbow Pitch Switch NO	53	Wrist Yaw Switch NO
11	Shoulder Pitch Resolver S2	32	Elbow Pitch Switch NC	54	Wrist Yaw Switch NC
12	Shoulder Pitch Resolver S4	33	Elbow Pitch Tach Generator +	55	Wrist Yaw Tach Generator +
13	Shoulder Pitch Switch NO	34	Elbow Pitch Tach Generator -	56	Wrist Yaw Tach Generator -
14	Shoulder Pitch Switch NC	35	Elbow Pitch Temp. Sig	57 - 59	Not Used
15	Shoulder Pitch Tach. Gen. +	36 - 39	Not Used	60	Wrist Roll Resolver S1
16	Shoulder Pitch Tach Gen. -	40	Wrist Pitch Resolver S1	61	Wrist Roll Resolver S3
17	Shoulder Pitch Temp. Sig	41	Wrist Pitch Resolver S3	62	Wrist Roll Resolver S2
18. - 20	Not Used	42	Wrist Pitch Resolver S2	63	Wrist Roll Resolver S4
21	Shoulder Roll Resolver S1	43	Wrist Pitch Resolver S4	64	Spare
				65	Spare

Figure 3 Connector and Pin Identification

Instrumentation Harness (DDMAM78P Connector on P-FMA)					
Pin No.	Identification	Pin No.	Identification	Pin No.	Identification
66	End Effector Spare				
67	Wrist Roll Tach Generator +				
68	Wrist Roll Tach Generator -				
69	End Effector Spare				
70	End Effector Spare				
71	Not Used				
72	All Resolvers R1				
73	All Resolvers R3				
74	All Switch C				
75	All Temp. -				
76	All Shields				
77 - 78	Not Used				

Figure 3 Connector and Pin Identification (continued)

Figure 3 (Continued)

	Power Harness (DCMAM37P Connector on P-FMA)				
Pin No.	Identification	Pin No.	Identification	Pin No.	Identification
1	Shoulder Yaw Motor+	32-37	Not used		
2	Shoulder Yaw Motor-				
3	Shoulder Yaw Brake-				
4	Shoulder Pitch Motor +				
5	Shoulder Pitch Motor -				
6	Shoulder Pitch Brake -				
7	Shoulder Roll Motor +				
8	Shoulder Roll Motor -				
9	Elbow Pitch Motor +				
10	Elbow Pitch Motor -				
11	Elbow Pitch Brake -				
12	Wrist Pitch Motor +				
13	Wrist Pitch Motor -				
14	Wrist Pitch Brake -				
15 - 19	Not Used				
20	Wrist Yaw Motor +				
21	Wrist Yaw Motor -				
22	Wrist Yaw Brake -				
23	Wrist Roll Motor +				
24	Wrist Roll Motor -				
25	Wrist Roll Brake -				
26	End Effector Motor+				
27	End Effector Motor-				
28	Slip Joint Spare				
29	Case Ground/Shields				
30	All Heaters -				
31	All Heaters and Brakes +				

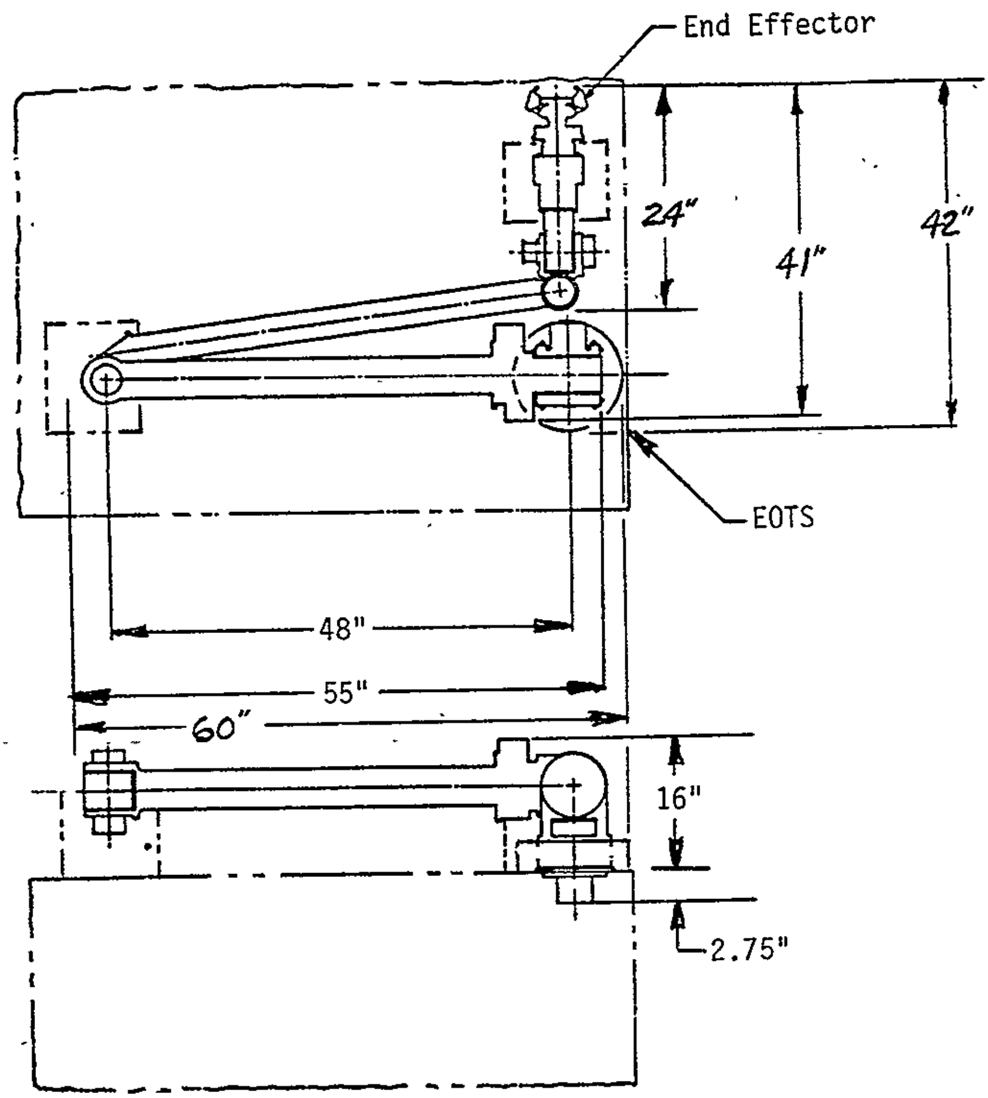


Figure 4 P-FMA Stowed Configuration

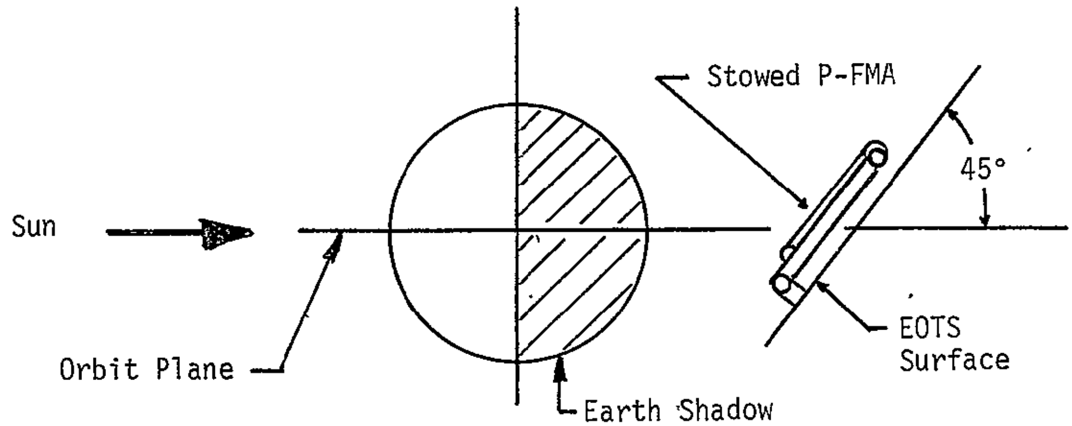


Figure 5 Stowage Mode, Cold Thermal Case

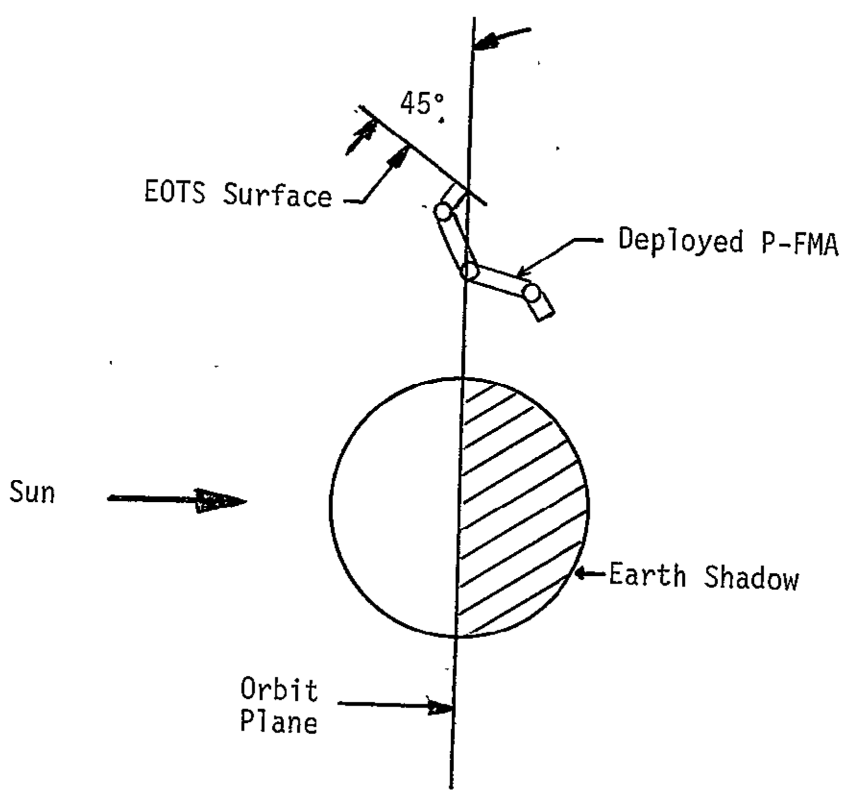


Figure 6 Deployed Mode, Hot Thermal Case

Table 1 P-FMA Weight Distribution

	WEIGHT (pounds)
SHOULDER YAW	17.2
SHOULDER PITCH	17.7
SHOULDER ROLL	12.0
UPPER ARM	4.8
ELBOW PITCH	11.0
LOWER ARM	3.3
WRIST PITCH	6.5
WRIST YAW	6.5
WRIST ROLL	7.6
END EFFECTOR (Parallel Jaw)	5.4
WIRE HARNESS	23.0
TOTAL WEIGHT	115.0 pounds

Table 3 Inland Motor Parameters

Parameters at 25°C	T-4471-G Shoulder Pitch, Yaw and End Effector	T-2218-A Shoulder Roll	OT-2911-A Elbow Pitch	OT-2143-A Wrist Pitch, Yaw and Roll
Peak Torque - lb. ft-T_p	1.5	.55	.85	.31
Viscous Damping-lb. ft/rad/sec	-	-	-	-
Zero Impedance Source-F_0	0.025	0.0101	0.013	0.0042
Infinite Impedance Source-F_I	0.001	0.00021	0.00005	0.00002
Rotor Inertia - lb ft sec^2-J_M	0.00053	0.000087	0.00023	0.000051
No Load Speed-rad/sec-W_{NL}	55	54	67	75
Weight - lb	1.5	1.25	1.5	0.7
Volts at Peak Torque, Volts-V_p	24.8	18.9	28.2	25.6
Amps at Peak Torque, Amps-I_p	4.55	2.2	2.74	1.3
Torque Sensitivity, lb ft/amp-K_T	0.33	0.25	0.31	0.24
Beck EMF, volts/rad/sec-K_B	0.45	0.35	0.42	0.33
DC Resistance, Ohms-R_M	5.45	8.6	10.3	20.0
Inductance, Henries-L_M	0.005	0.0122	0.017	0.019
Current Limit, Amps max-I_M	2.7	1.25	1.75	0.8
Gear Ratio - N	109.8:1	66:1	103.1:1	86.4:1

Table 4 Inland Tach Generator Parameters

Parameters at 25°C	TG-1338-A, All Joints
Friction Torque - oz. in. - T_F	0.7
Ripple Voltage-Volts (avg to peak)-V_F	2.0
Ripple Cycles - cycles/rev.	31
Rotor Inertia - oz. in. sec^2-J_G	8.8×10^{-4}
Weight - oz	4.3
DC Resistance - ohms - R_G	71
Sensitivity - volts/rad/sec - K_V	.12
Inductance - henries - L_G	.024
Load Resistance - ohms min. - R_L	6.5K
Operating Speed-rad/sec max. - W_M	200
Volts at max speed - volts - V_M	24
Voltage Limit - volts - V_L	2.64 for shoulder yaw and pitch 4.94 for elbow pitch 2.09 for wrist pitch, yaw, and roll 1.58 for upper arm roll

Table 5 Position Feedback Parameters

Typical Electrical Data	Shoulder Yaw and Pitch and Upper Arm Roll	Elbow Pitch and Wrist Pitch, Yaw and Roll
Primary	Rotor	Rotor
Rated Primary Voltage	26V	26V
Test Voltage R_1 to R_3	26V	26V
Rated Frequency	400 Hz	400 Hz
Primary current (nominal)	0.246A	0.250A
Primary power (nominal)	2.6W	1.0W
ZRO rotor impedance (stator open circuit)	43.3 + J96.4	204 + J388
ZRS rotor impedance (stator short circuit)	56 + J29.4	367 + J284
ZSO stator impedance (rotor open circuit)	14 + J29.75	168 + J110
ZSS stator impedance (rotor short circuit)	12.4 + J4.65	171 + J42.6
Output Voltage	11.8	9.54
Transformation ratio ± 0.015	0.454	0.367
Sensitivity (volts/deg)	0.206	0.167
Phase shift input to output (open circuit)	16.4 deg	14 deg
Rotor DC resistance	15.7 ohm	42 ± 6 ohm
Stator DC resistance	5.4 ohm	92 ± 6 ohm
Accuracy (maximum error from synchronous to zero)	2.5 minutes	2.5 minutes
Weight, nominal	9.2 oz	20 oz
Rotor moment of inertia	12 gm-cm^2	190 gm-cm^2

<u>Degrees of Resolver Rotation/Degrees of Drive Joint Rotation</u>

Shoulder yaw - 335°/400°
Shoulder pitch - 355°/180°
Shoulder roll - 339.4°/180°
Elbow pitch - 348.4°/280°
Wrist pitch and yaw - 328.7°/180°
Wrist roll - 360°/360°

Table 6 Brake Electrical Characteristics

Brake Electrical Parameters	Units	Brake Part Number		
		BFR-10H (Wrist Drives)	BFR-20D-1 (Elbow Drive)	BFR-20D-2 (Shoulder Drives)
Design Voltage	Volts	24.0	24.0	24.0
Coil Resistance	Ohms ±10%	96.0	75.0	75.0
Pull-in Voltage (at 20°C)	Volts (max)	17.0	17.0	17.0
Holding Voltage (at 20°C)	Volts (max)	8.0	8.0	8.0
Current Response (1)	msec	19.0	25.0	25.0
Inductance (2)	henries	1.0	1.8	1.8

NOTES: (1) Time required to reach 63% of maximum current with 0.007-inch gap (brake face clearance)

(2) With zero gap using 1,000 Hz

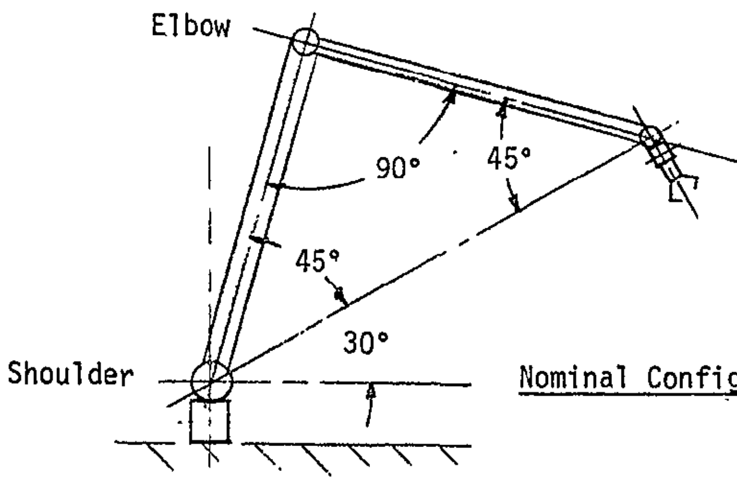
Table 7 Heater Resistances

Heater	Watts ±10%	Resistance ohms ±10%
E1CX3A (Wrist Drives)	5.5	120
G1JX154A (Elbow and Shoulder Roll)	7.8	82
G1NX7A (Shoulder Drives)	11.0	52

Table 8 Mass Moment of Inertia around Jointy - slug-feet²

NOMINAL CONFIGURATION

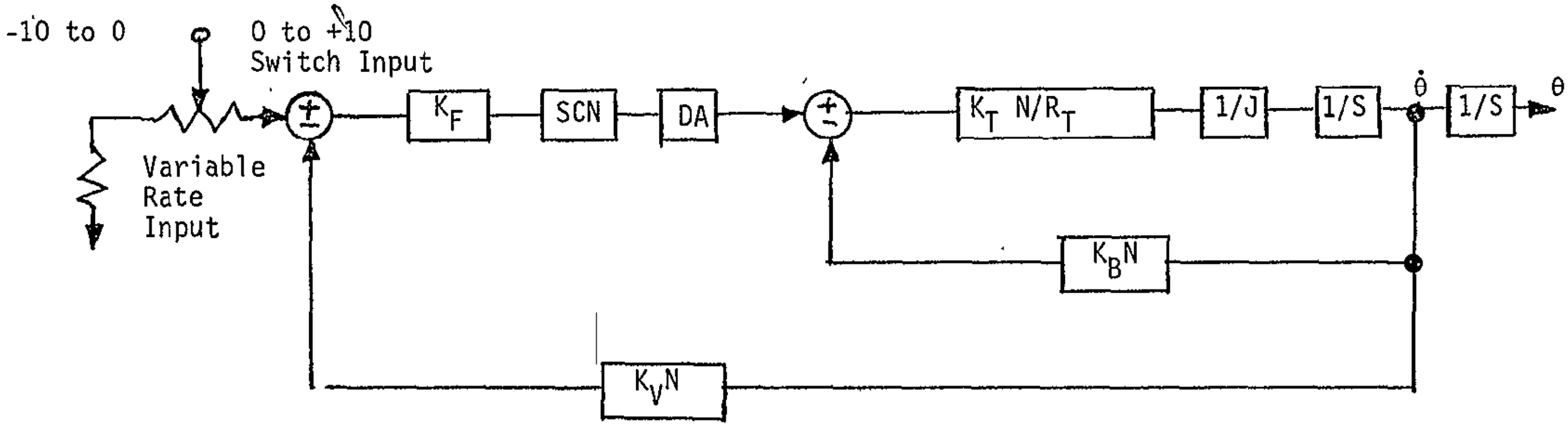
DRIVE JOINT	UNLOADED	LOADED (110 LB MASS)
Shoulder Yaw	22.000	153.42
Shoulder Pitch	34.741	167.67
Elbow Pitch	15.691	142.29
Wrist Pitch	0.522	24.15
Wrist Yaw	0.267	18.58
Wrist Roll	0.0029	2.28
ARM STRAIGHT OUT		
Shoulder Pitch/Yaw	68.367	447.28



Nominal Configuration

Table 9 Mass Moment of Inertia of Joint Drives - slug-feet^2

JOINT	FORWARD DRIVE	BACKDRIVE
WRIST	6.689×10^{-5}	0.4994
ELBOW	2.991×10^{-4}	3.178
SHOULDER	6.623×10^{-4}	7.976



DEFINITIONS

Determined by Component Selection and Design

K_T = torque sensitivity of motor, ft-lb/amp

N = gear ratio

R_T = total resistance, ohms

J = total reflected inertia, ft-lb-sec^2 (loaded and unloaded)

K_B = back EMF of motor, volts/rad/sec

K_V = tachometer sensitivity, volts/rad/sec

K_F = forward loop gain

SCN = servo compensation network

DA = drive amplifier

Figure 7 Rate Servo Loop Block Diagram for Each Joint

Appendix C

APPENDIX C

Operations, Calibration, and Maintenance

Document

for the

Proto-Flight Manipulator Arm (P-FMA)

April 1977

Prepared by:

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Denver Division
P.O. Box 179
Denver, Colorado 80201

C

OPERATIONS, CALIBRATION AND MAINTENANCE

1.0 GENERAL OPERATIONS

General guidelines and precautions for proper handling and operation of the P-FMA are identified below.

1.1 During handling of the P-FMA the electrical power should be removed from all brakes so that the brakes are set on all drives. During transportation the brakes should be set, the arm folded back on itself, i.e., stowed configuration, and supports placed at the shoulder drives, the elbow pitch drive, and at the wrist drive to prevent motion and possible damage.

1.2 Set-up of the arm for operation should always be accomplished with brakes set. The support structure at the shoulder yaw interface should be leveled in both directions to minimize the gravity imbalance in the yaw directions.

1.3 During operation the voltage to the resolver should be set at 26.0 Vac at 400 Hertz. The voltage regulation should be consistent with the desired accuracy of the output voltage or a ratiometer for output to input can be used to correct for input voltage variations.

1.4 During operation of the P-FMA care must be exercised to not overheat the motors. The table below lists the voltages, and resulting currents at room temperature, to develop full stall torque or no load speed. It is recommended for long term earth and vacuum chamber operations that voltage and currents not exceed 110% of these values.

Drive	Voltage	Current-amps
Shoulders & End Effector	24.8	4.5
Shoulder Roll	18.9	2.2
Elbow	28.2	2.7
All Wrists	25.6	1.3

1.5 When it is desired to allow a drive to be back driven the electrical power at 28 Vdc must be applied to release the brake. The brakes are designed to restrain stall torque of the motors at rated voltage and must be released for operation.

1.6 Micro switches are located at each extreme of travel on each drive except the wrist roll. For safety these switches should be wired into the motor control circuitry, manual or automatic, to interrupt power to the motors. This precaution is necessary to prevent structural hardstop contact at the extremes of travel and to preclude damage to the external wire harnesses.

1.7 When operating the jaws of the end effector a low voltage, ≈ 5 Vdc, should be used to open or close the jaws. If more jaw grip force is desired the voltage can be increased up to the maximum after contact is made. The jaws can be damaged if they are driven together at maximum velocity.

1.8 All the drives except shoulder roll and end effector are backdriveable at reasonably slow speeds. Damage to the arm will occur if it is driven against a rigid object at high speeds as the safe gear stress value can be exceeded from impact loads.

1.9 Electrical connection only be made through the two base connectors or through the individual drive joint electrical connectors. Special breakout boxes are available for interfacing with these connectors in order to power the drives or to perform diagnostics. A full set of drawings, wiring diagrams, and schematics are on file at NASA-MSFC and MMC. An "as-run" acceptance test procedure with electrical test data is also on file.

1.10 All of the drives have an inherent no load analog voltage threshold (less than 10% of rated voltage) to produce motion in one direction. To reverse direction, approximately the same analog voltage of opposite polarity will be required. Therefore, if the motor voltage drive source is analog this total hysteresis band must be considered in the control response required. Pulse width modulated controls can minimize this hysteresis effect.

1.11 Except for checkout, the heaters should not be used unless a cold test is being performed. In any case the temperature sensors in the pitch drives should be monitored so that the maximum allowable operating temperature is not exceeded.

1.12 If another end effector is used the wiring schematics must be utilized to assure proper pin to pin connections thru the slip ring on the wrist roll drive. Note that certain of the slip ring conductors, numbers 1 and 8, can carry up to 10 amperes, while the other six can only carry up to 1.0 amperes.

1.13 In the use of the P-FMA with the counterbalances, it must be recognized that this added weight causes large increases in the reflected moments of inertias on the drives from the arm. Accelerations will be significantly reduced, thus reducing the control response. Conversely the deceleration distance will be increased substantially and must be considered to prevent overtravel to hard stop. If the P-FMA is used in a closed position loop system, extreme care must be taken so that the added inertias do not cause an instability. Driving the system at or near resonance could cause damage to the drives or the arm.

1.14 With the counterbalances installed the arm is capable of performing in most orientations at full travels of each drive. However, there are a few operations, such as the fully stowed configuration, that are degraded or restricted. The imbalance to the arm is insignificant for wrist yaw travels up to $\pm 20^{\circ}$; however, beyond 20 degrees some type of compensation should be considered. In some operations, such as the stowed position, the counterbalance will interfere with the arm and prevent full travel. If the shoulder roll is rotated from the normal orientation, the wrist yaw becomes a pitch degree of freedom and it is not counterbalanced. These special considerations should be used as restrictions to manual or automatic control of the arm.

1.15 General engineering practices were employed in the arm design to reduce electromagnetic interference (EMI). The external harnesses have individual conductor shields, and these are terminated thru a pin on each of the two main base connectors. These shields should be grounded at the controls ground. Internal to the drives it was not physically possible to complete the shielding to each component. This will be accomplished at refurbishment by the use of single shielded conductors and flexible circuits with shield planes. The motor circuits should contain EMI filters to ground; for these reasons some noise coupling might occur. As part of a flight refurbishment, it is suggested that EMI criteria and tests be performed to ensure compatibility with the RF command link. At that time appropriate action such as adding more wire shielding, elimination of internal micro-connectors, providing conductive connector housing, and providing filters at the motors will be incorporated.

2.0 CALIBRATIONS

2.1 When the P-FMA is relocated, the arm should be placed into an approximate stowed configuration. With the shoulder, elbow, and wrist drives supported, the counterbalance weights can then be removed. When the arm is set-up and leveling has been accomplished, the counterbalance weights should be carefully re-installed and the arm recalibrated. This is accomplished by releasing each brake, one at a time starting at the wrist pitch, and adjusting the counterbalance weights until the gravity effect is counteracted. Then a minimum voltage should be applied to the drive; and the operating rate from the tachometer, recorded. With the polarity reversed, the rate of travel should be approximately the same in the opposite direction. If it is not counterbalance weights should be adjusted.

All changes to the counterbalanced manipulator should be carefully planned and analyzed before implementation. Verification tests should be performed at minimum voltages to checkout the new configuration.

2.2 If it is planned to use the resolver outputs for position information for any particular task, an end-to-end calibration is recommended. Internal adjustment of the resolvers with respect to an arbitrary mechanical point on the drive is not only unnecessary but is not desirable. In most cases the minimum voltage from one output was adjusted to coincide with a "null" or reference position in the Interface Control Document. To calibrate for a given task the minimum voltage of either output or an equal voltage from both outputs (resolver position at 45°, $\sin 45^{\circ} = \cos 45^{\circ}$) can be used as the starting reference.

Then the drive rotational travel and respective voltage changes can be measured as the calibration. It should be noted that the gearing ratios between the drive and the resolver are presented in the Interface Control Document. As a general rule, we had designed to have nearly one rotation of the resolver to correspond with the total specified travel of each drive joint.

3.0 MAINTENANCE

3.1 From a functional standpoint the P-FMA has been designed to be maintenance free. The gears and bearings are lubricated for earth ambient operation for the specified number of hours.

3.2 The P-FMA drive motors and tachometers were assembled with silver-graphite brush material for long life at earth ambient operation. If vacuum operations are required, alternate brush ring assemblies made from the Boeing 046-45 material must be used. Caution: Do not operate motors or tachometers for more than 15 seconds in an earth ambient with the Boeing brushes. During the preflight refurbishment of the P-FMA, the standard brushes will be replaced with the Boeing brushes. Additionally, the existing lubricant for all gears and bearings may exhibit high outgassing characteristics in vacuum operations. The preflight refurbishment is intended for the purpose of replacing this grease with a space compatible lubricant, Braycote 3L38-RP.

3.3 The internal and external harnesses have been designed for convenience and accessibility and long life for earth operations. They will not require any maintenance unless damaged. During the refurbishment for flight the wiring should be replaced as described in paragraph 1.15.

3.4 For cosmetic purposes any external P-FMA scratches can be "touched-up" by brush application of the white acrylic lacquer supplied with the arm.

Appendix D

APPENDIX D

PROTO-FLIGHT MANIPULATOR ARM DRAWING TREE

Proto-Flight Manipulator Arm Assembly (8 ft)	849PFM00000-009
Proto-Flight Manipulator Arm Assembly (4 ft)	849PFM00000-010
Proto-Flight Manipulator Arm Schematic	849PFM00100
Proto-Flight Manipulator Arm Harness Assembly	849PFM00200
Proto-Flight Manipulator Arm Harness Machined Details and Assys.	849PFM00201
Joint Actuator - Shoulder Yaw	849PFM01000
Shoulder Yaw Schematic	849PFM01100
Shoulder Yaw Harness Assembly	849PFM01200
Actuator Harness Machined Details	849PFM01201
Connector Assys	849PFM01210
Cable Assys, Flat	849PFM01220
Shoulder Pitch and Yaw Housing Assemblies	849PFM01300
Shoulder Pitch and Yaw Machined Details	849PFM01301
Shoulder Drive Gears	849PFM01401 thru 849PFM01407
Joint Actuator - Shoulder Pitch	849PFM02000
Shoulder Pitch Harness Assembly	849PFM02200
Shoulder Pitch Schematic	849PFM02100
Joint Actuator - Shoulder Roll	849PFM03000
Shoulder Roll Schematic	849PFM03100
Shoulder Roll Harness Assembly	849PFM03200
Shoulder Roll Machined Details and Assemblies	849PFM03300
Shoulder Roll Gears	849PFM03401
Arm Section Components	849PFM04000
Joint Actuator - Elbow Pitch	849PFM05000
Elbow Pitch Schematic	849PFM05100
Elbow Pitch Harness Assembly	849PFM05200

Elbow Pitch Housing Assembly	849PFM05300
Elbow Pitch Machine Details	849PFM05301
Elbow Pitch Gears	849PFM05401 thru 849PFM05406
Joint Actuator - Wrist Pitch and Yaw	849PFM07000
Wrist Pitch and Yaw Schematic	849PFM07100
Wrist Pitch and Yaw Harness Assembly	849PFM07200
Wrist Gears (Pitch, Yaw, and Roll)	849PFM07401 thru 849PFM07406
Joint Actuator - Wrist Roll	849PFM08000
Wrist Roll Schematic	849PFM08100
Wrist Roll Harness Assembly	849PFM08200
Gear Drive Assemblies - Wrist Pitch, Yaw, and Roll	849PFM08300
Wrist Drive Machined Details	849PFM08301
End Effector Assembly	849PFM09000
End Effector Schematic	849PFM09100
End Effector Harness Assembly	849PFM09200
End Effector Machined Details and Assemblies	849PFM09300
End Effector Spiroid Gear Set	849PFM09401
Interface Control Document	ICD-PFM-00000
Contract End Item Specification	CEI-PFM-00000