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# SPACE STATION END EFFECTOR STRATEGY STUDY

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# I. INTRODUCTION

Space Station level B has recognized the growing number of references to end effectors and end effector tasks that are appearing in contractor and Level C reports. Currently, end effectors are expected as part of the Japanese Experiment Module, on the Mobile Service Center (or Mobile Remote Manipulator System), the OMV, the Service Bay, and NSTS. The Flight Telerobotic Servicer (currently in the definition phase) and its associated end effectors are treated as a unit for purposes of this study. As the Space Station Program evolves, it is to be expected that the need for space manipulation systems and techniques will be identified and their fulfillment will come from these, and other sources.

In order to avoid duplication of effort, unnecessary logistics and sparing, complex interfaces and cost impact, the Level B has commissioned a study to provide a definition of end effector terms, to collect and identify program functional requirements and tasks for end effectors, to provide an assessment of current state-of-the art in end effector technology, and to provide some guidance to the Space Station Program in developing a strategy for end effectors and their development.

To that end an ad-hoc working group was formed with participation from Work Package Level C, Level B, international partners, and JPL and LaRC. Langley provided the lead and background work to integrate inputs from the other participants.

The approach taken for the study was to survey all program documents down through the Data Book level to identify requiremenets for end effectors, to survey through known sources all end effectors reasonably related to potential space use, and then to form a comparative assessment of the available technologies and the program requirements as currently understood. From the comparative assessment a set of program options have been developed for a program-wide end effector strategy. As a part of the study, a definition of terms has been developed that will form a part of a Change Request (CR) to begin the process of institutionalizing the strategy developed from the Study.

# II. DEFINITIONS

In order to facilitate the study, both in developing requirements and in matching those requirements to the available technology in end effectors, a series of definitions were proposed to the working group. These definitions served as the basis of a CR for the Program Definition and Requirements Document (PDRD) JSC document 30000) which will eventually include the structure around which end effector requirements and strategy will be formalized.

## Initial Definition

1. For purposes of definition, it will be assumed that an end effector is part of some remote manipulating system. This remote manipulating system will be assumed to be one of two major types:

a. Compound Assembly, disconnectable on-orbit or at-ground payload integration facilities

b. Integral Assembly, not separable into subassemblies

2. Definitions will be applied to type (a) - compound remote manipulator systems, hereafter referred to only as remote manipulator systems.

3. Each remote manipulator system will, by definition, be described as having three parts:

(1) Transport assembly (for translation and rotation)

(2) Manipulator Assembly (for positioning)

(2) End Assembly (for performing function)

4. To recognize that remote manipulator systems can be cascaded in serial, manipulators will be counted out from the major support structure, strong back, etc., on the Space Station, OMV, etc.

5. Thus, two arms in cascade (serial) would have the one attached to the Station, OMV, etc., called Level 1 and the next one Level 2.

6. The manipulator assembly is defined as that part of the remote manipulator system that performs the positioning role, but is incapable of performing any task function such as grappling, welding, attaching, etc.

7. The end assembly associated with a particular level of manipulator either performs a task function or provides an interface.

8. The small adjustments in location below that possible by the manipulator are not considered manipulator positioning.

9. The end assembly will be defined as that structure which performs functions and is one of three types:

(1) Simple

(2) Compound

(3) Complex (System)

Simple A simple End Assembly consists of a direct connection of

(1) Holders - Devices to hold, position, or move a Space Station Program Element (SSPE) but does not repair or modify it.

(a) Snare
(b) Magnetic/Spring-loaded
(c) Grippers
expandable
contractable

(d) Inflatable
(e) Nets
(f) Screw pneumatic/hydraulic
(g) Others

(2) Tools - Devices that physically act upon an SSPE to repair or modify it.

(a) Welder
(b) Riveter
(c) Nut/Screw driver (Powered or Unpowered)
(d) Positioner
(e) Pull-twist and push-twist tools
(f) Umbilicals
(g) Other

(3) Sensors

(a) TV Cameras
(b) Gas Sensors
(c) Thermal Sensors
(d) Range Detectors
(e) Tactile (pressure/torque) sensors
(f) Other

(4) Adapters

(a) Quick change unit
(b) Interface plate
(c) Other

Compound End Assembly - Assembly adapters/holders and/or simple End Assemblies but no additional manipulators.

Complex End Assembly - One or more additional levels of manipulator (positioners) plus End Assembly (simple, compound, or complex.)

Compound/Complex - Composed of a compound end assembly holding a complex (manipulator - containing) end assembly. The compound part is assigned to the lowest level manipulator.

Flight Telerobotic Serivcer - The primary robotic system in the Space Station Program, intended to be supported by any of several manipulator arms or the OMV, or to be operated on the Space Station while independent of any transport assembly. It is composed of three primary subsystems: A control console, the robot, and the computer command and control system.

End Effector - The final assembly that performs the task function.
Definition Pertinent to End Assemblies:

(1) Degree of Freedom: The number of rotational or translational axes through which motion can be obtained.

(2) Holders: Holders physically grasp and manipulate objects at the work site (JPL/Mishkin and Jau 12/10/85).

(a) Grippers: Holders with clamping capabilities in one direction or in one plane only. Grippers are a clamping device only (JPL/Mishkin and Jau).

(b) Multi D.O.F. Holders: Possess more than one D.O.F. but do not have manipulative capabilities. (JPL/Mishkin and Jau).

(c) Manipulative Holder: A hand-like manipulative device.

(d) Smart hands: Holders capable of recognizing some of their environment, load conditions, and clamping characteristics (JPL/Mishkin and Jau).

(e) Quick change unit: The device which couples the end assembly to the manipulator arm permitting the capability to change end effectors in flight. (Adapted from LEMSCO-21012).

## III. REQUIREMENTS

In order to develop any strategy with respect to end effectors, the Space Station functions that require them must be identified. The latter is complicated by the fact that many of the program requirements are high level and at least some of the end effectors required to support a particular function must be derived by inference.

Chief among the documents that would be expected to contain requirements for end effectors is the Program Definition and Requirements Document, PDRD, which is the major governing source. The PDRD is composed of a series of controlled documents which constitute program policy and backing them up are the Data Books, which are not program policy. The approach of this study has been to attempt to extract requirements first from the PDRD, then from pending Change Requests, CR's, and then from the Data Books, and in that order. At each stage the pedigree for the requirement has been retained so that its status with respect to program baseline is clear.

It should be recognized that the process of developing the PDRD is not uniform, and, for various reasons, some areas are less well developed than others. Note is taken of the unevenness to emphasize the fact that the results of a study like this will require reconsideration from time to time as the PDRD becomes a unified whole.

After identification, the conceptual end assemblies implied or stated in the requirements sources, were partitioned along the lines of the classes of Simple End Assemblies: Holders, Sensors, Adapters, and Tools. Within the Holders, a subdivision was made that recognized the somewhat institutional role the standard end effector, SEE, and the standard grapple fixture, SGF, have played in past practice and are likely to play in the future.

In fact, the PDRD and Customer Servicing Requirements Data Book JSC 30222 contain several references to the SGF as the primary interface point between Space Station MRMS:

| | |
|---|---|
| Hubble Space Telescope | 2.2.1.1.6.B |
| Space Infrared Telescope Facility | 2.2.2.1.8.B |
| Advanced X-Ray Astronomy Facility | 2.2.3.1.6.B |
| Gummor Ray Observatory | 2.2.4.1.6.B |
| Solar Maximum Mission | 2.2.5.1.6.B |
| Space Station Spartan | 2.2.6.1.7.B |

The degree to which the above influences the requirements for end assemblies will be evident in the data to be presented in the various end assembly categories.

## Holders - (SGF Compatible)

Requirements taken from PDRD

2.1.2.4.3.10.E ELECTRICAL POWER FOR PAYLOADS

The MRMS shall be capable of providing at least TBD kW of electrical energy across the MRMS-to-payload interface. Peak power shall be at least 1.8 kW. Voltage and frequency shall be TBD.

Discussion: Spacecraft to be serviced may be too large to be carried by the SGF while attached to the transporter, or may require power while being handled. End assembies must be capable of supplying 1.8 kW peak to payloads.

2.1.2.4.3.2.3 HOLDING FIXTURES

For the user systems and ORU carriers, the restoration capability shall include holding and handling fixtures which are compatible with STS payload trunnions, flight support system fittings, and grapple fittings.

Discussion: This section implies that user systems and ORU carriers must have grapple fixtures and, if that is so, there must be a Holder end assembly capable of operating with the SGF and where exchange from manipulator to manipulator or fixtures is involved, both must be capable of handling the SGF. This also means that an SEE or other SGF-compatible holder is required on all manipulators or recipients of ORU's, service, etc. and multiple SGF's on ORU's.

3.5.1.3.3 GRAPPLE FITTINGS

The Space Station shall have the capability to mechanically attach free-flying satellites for handling using the STS grapple fittings on the payloads.

Discussion: Holders will be provided on all Space Station Systems which are involved with free-flyers that have SGF's, and the free-flyers are not required to have any other type of interface to Space Station to guarantee mechanical attachment.

Requirements taken from Change Requests

2.2.5 MANIPULATOR OPERATIONS

2.2.5.1 The MRMS shall be capable of removing the contents of the Orbiter cargo bay while the NSTS is attached to the Station and provide delivery access to any external portion of the Station.

Discussion: This implies that the end assembly must be capable of grappling the SGF that the NSTS uses.

2.2.5.6. The MRMS shall be the primary method of berthing the logistics modules to a Station port. An alternate method shall be provided.

Discussion: To berth the Logistics Module, the MRMS must provide means for grappling. Since it came out of the NSTS, the interface must be an SGF.

2.2.5.8 The MRMS shall be capable of retrieving, berthing, and deploying free-flying vehicles having the required standard grapple fixture(s).

Discussion: This requirement implies that an SGF is needed for retrieving, berthing, and deploying free-flying vehicles.

2.1.9.11.2 All ORU's installed in non-pressurized areas shall be designed to be compatible with EVA and remote manipulating device operations.

Discussion: This CR requires compatibility of Holders with ORU's and, simultaneous ORU compatibility with EVA. This dual requirement implies a definition and assessment of Holder options such as SGF's on ORU's, EVA handles on ORU's, or EVA-Holder compatibility, etc. This also opens up the question of size of ORU's or ORU carriers and the whole area of SGF's, ORU's, and ORU sizing strategy compatible with both EVA and remote manipulating device capabilities.

Requirements taken from Data Books

Pages 4H-8,4H-10,4H-12 and 4H-23 of the Data Books show the hardware schematic for the solar Alpha Joint, Beta Joint, coarse pointing system (CPS) and the Radiator Rotary Joint, respectively. All the schematics show the use of the SGF. These schematics are reproduced in Appendix A.

## Holders - General Types

Requirements taken from PDRD

2.2.2.2.2.2.8 MOBILE FOOT RESTRAINT (MFR)

Each MFR shall be positionable and shall support, with suitable restraint, one pressure-suited astronaut with supporting EVA equipment. Two MFR's are required.

Discussion: Even though at first glance the MFR might not be considered a Holder, or perhaps even end assembly, the MFR is nevertheless a flight qualified device which performs an end assembly role in carrying the astronaut. The future role for the MFR, which may be more extensive than is supportable by the current device, must be considered.

2.2.5.2 A Manipulator Foot Restraint (MFR) compatible with the MRMS shall be provided.

Discussion: As noted above the MFR has a potential role considerably beyond the simple device it represents today. As part of the Mobile Service Center version of the MRMS, the MFR plays a role of Control Center for the MSC and thus has complex interfaces with the manipulator arm.

2.2.2.2.2.1.A ASSEMBLY

The MRMS shall support the Space Station assembly by providing support for initial truss construction, providing transport of contruction elements, providing autonomous operation independent of Space Station power for periods up to TBD hours, and by providing Mobile Foot Restraints (MFR's) for astronaut support of assembly tasks.

Discussion: Support for truss construction implies the ability to hold structural members, either in cases or individually. Holders are implied either SGF compatible or non-SGF compatible. Carriers for structural elements might have SGF's, but individual elements might be more effectively handled by gripper-like small holders. Also, certain structural elements such as radiator fins/elements might not be capable of supporting an integral SGF, and might need either a quick disconnect adapter-holder or holder capable of grasping with simpler means such as Velcro or magnetic.

3.2.4 DEPLOYMENT, ASSEMBLY, AND CONSTRUCTION

The Space Station Program (SSP) will provide support capability for construction, assembly, and deployment which implies providing payload service devices such as manipulators, Manned Maneuvering Unit (MMU)'s, Extravehicular Activity (EVA) capability, and standard tool kits. The manned element will have facilities to support the assembly and disassembly of large structures including attachment provisions, a storage area for components, a remote manipulator system, and orbital maneuvering system. Power, thermal, and data system interfaces will be available to the payload undergoing assembly or disassembly. The platforms will also be designed to facilitate on-orbit assembly and disassembly.

Discussion: General requirement for holders to support assembly as well as standard tool kit.

3.2.8 PROXIMITY OPERATIONS

Payloads capable of maneuvering themselves may propel themselves to and from the station; however, they shall not operate within zone 1 ( a 1 km sphere about the space station.) The OMV or crew with a MMU will be used to bring payloads in and out of zone 1.

Discussion: Requirement for capture device compatible with EVA-MMU and OMV which may be in addition to the SGF, since some payloads may not have the SGF (uncooperative spacecraft or damaged spacecraft or tumbling spacecraft, etc.)

2.1.2.4.3.10.B GRAPPLING

The MRMS shall be capable of grappling a payload having motion as specified in paragraph 2.2.2.2.1.4. [Paragraph 2.2.2.2.1.4 refers to a spacecraft having the possiblility of motion about several axes or directions--an unstable spacecraft.]

Discussion: Some sort of end assembly capable of attaching to, and despinning tumbling or disabled spacecraft is required--such as a net-like or collaring end assembly that can be operated remotely to reduce the potential hazard to an astronaut in EVA.

Requirements taken from Change Requests

2.2.5.2 A Manipulator Foot Restraint (MFR) compatible with the MRMS shall be provided.

Discussion: As noted above the MFR has a potential role considerably beyond the simple device it represents today. As part of the Mobile Service Center version of the MRMS, the MFR plays a role of Control Center for the MSC and thus has complex interfaces with the manipulator arm.

Requirements taken from Data Books

Page 2A-300 of the Data Books shows an assembly method of the Space Station (See Appendix A). An MSC/MRMS work station to control assembly near the work area is implied. This work station having a variety of devices such as controls, TV cameras, sensors, etc. would be classified as a compound end assembly. Also, specially shaped end assembly holders are needed for the assembly manipulator to handle the various components of the assembly such as tubes, nodes and grapple fixtures.

Page 4K-55 of the Data Books is a reference to the Space Station assembly and implies a requirement for various special type end assemblies such as holders, tools, sensors (See Appendix A). Whereas no strong defintion of the end assembly is made, interchangeability and quick disconnects would be required on orbit to efficiently switch between the various assembly task and minimize the assembly time.

## Sensors

Requirements taken from PDRD

2.1.2.4.1.2.1 INSPECTION

The SSP shall provide the capability for inspection of user systems either remotely or by EVA.

Discussion: This PDRD entry indicates that sensor end assemblies are required. Inspection can be contact (ultrasonic, X-ray, sonic, temperature, vibration, etc.) or non-contact ( television, gas sensors, illuminators, radiation detectors, etc.) MRMS would apppear to be the carrier, but EVA astronaut, OMV, or remote flying EMU might equally serve equally as well.

2.2.4.2.3.4 LEAK DETECTION [Thermal Control System]

A method for detecting, isolating, and repairing leaks within the system shall be provided.

Discussion: Detecting, isolating, and repairing imply the need for sensors to detect leaks in thermal control system (TCS) ammonia and a method for repairing (i.e., Tool-type end assembly).

2.2.2.2.2.2.9 VIDEO AND LIGHTING

The MRMS shall supply video and lighting to support handling of payloads, for precapture inspection of payloads, for remote viewing of EVA work, and for remote inspection of parts of the Space Station from the IVA station.

Discussion: A clear requirement for illumination and video (multispectral imaging, laser assisted or conventional lighting, thermal imaging, gas sensing, etc.) precapture inspection. This requirement is further support to paragraph 2.1.2.4.1.2.1 above.

Requirements taken from Change Requests

2.8 A "bar-code reader" type device shall be provided which shall allow for automatic reading of the label system. On-orbit Maintenance and Operations Requirements Document (OOMORD.)

2.9 The "bar-code reader" type device may use color codes or bar codes or some sort of interpretation device. (OOMORD.)

Both of these are a requirement for an assembly with integral lighting to interpret codes. Such an end assembly might be small enough to be carried by an astronaut or operated remotely, or both.

2.2.5.7 The MRMS shall have collision avoidance capability for all operations including NSTS payload bay operations and operations within the Station truss.

Discussion: A proximity sensory capability, probably integral to the MRMS, but possibly in the form of an adapter or compound end assembly is required.

4.8.B Orbital Support Equipment

The statements contain the requirement for "3) Diagnostic, Checkout, and Monitoring Equipment." This implies the need for end assemblies to support these tasks.

Requirements taken from Data Books

Fire suppression, noted in paragraph "h" on page 4I-18 of the Data Books, (App. A) implies the need for a remotely operated end assembly for this hazardous operation. Fire suppression is too dangerous for EVA and the task would probably heavily rely on the MSC/MRMS. Remotely operated end assemblies with sensors for leak detection in the hazardous propellent areas would also be required. Holders would have to be provided to handle fire extinguishing systems.

## Tools - Umbilicals

Requirements taken from PDRD

2.1.2.4.3.4 FLUIDS REPLENISHMENT SYSTEM

The SSP shall provide a TBD capability for replenishing consumable fluids. Hazardous fluids shall be replenished using remotely operated equipment with manual overrides. Conditioning and transfer equipment shall be designed to minimize leakage in accordance with the requirements in paragraphs 2.1.11.2 and 2.2.12.2.

Discussion: This implies a fluid transfer device umbilical for hazardous fluids transfer, either an integral end assembly or as an adapter, that may temporarily detach from the manipulator arm or operate attached.

In addition, leak detection is implied which can be detected by sensors integral to the umbilical end assembly or incorporated in an auxiliary sensor end assembly.

3.2.5.2 ELECTRICAL POWER FOR PAYLOADS

The OMV (or OMV plus interface kits) shall be capable of providing TBD kW hours of electrical energy across the OMV to payload interface. Peak power shall be 1.8 kW. Voltage shall be 28 volts direct current (dc.)

Discussion: This requirement implies need for an umbilical to transfer power across interface. That interface may be the Standard Electrical Grapple Fixture (SEGF) or a separate port for umbilical support.

2.2.4.2.3.1 THERMAL CONTROL SYSTEM (TCS) INTERFACES

The thermal design shall easily interface with equipment, modules, and payloads. The interface shall not, where practical, require making and/or breaking of fluid connections for maintenance and refurbishment or experiment installation.

Discussion: Payloads may require thermal control either by supplying heat, or by removing waste heat. The "no making and/or breaking" of fluid connections may imply a thermal umbilical or cold/hot plate end assembly.

Requirements taken from Change Request

2.2.2.2.6.1 Capacity - Provide a family of mechanisms capable of accommodating a range of connector quantities, sizes, and types.

2.2.2.2.6.2 Type of Operation - Provide remotely operated and manually operated umbilicals.

2.2.2.2.6.3 Actuation - Remote operation shall be provided by electromechanical actuators. Manual operations shall be compatible with EVA requirements.

2.2.2.2.6.4 Misalignment - Misalignment capability for the remotely operated umbilicals is TBD.

Discussion: This is further support for the requirement that end assemblies will be needed for the job of umbilical operation.

2.5.1.16 Diagnostic procedure shall include preinstallation checkout of ORU's.

Discussion: Preinstallation checkout of externally stored ORU's require either a DMS link external to the modules, or a power and communication link to DMS, or umbilical end assemblies to power the ORU diagnostic systems, activate them, and link to DMS through the already provided link through the end assembly.

Requirements taken from Data Books

2.2.2.3 Umbilical to OMV

Umbilical(s) shall be provided between OMV accommodations and the OMV to provide power, data, and fluids. Mating and demating of the umbilical shall be performed robotically without the need for EVA.

Discussion: This is additional support for an umbilical end assembly, simple or compound, to use with hazardous fluids, gases, etc., in addition to data, power, etc. An important point is that this end assembly is for OMV, not just Space Station, and implies attention should be given to Space Station compatibility to already designed related systems e.g., OMV.

Umbilical requirements are given on pages 4H-44, 4H-45, and 4H-46 of the Data Books (See Appendix A). As shown, remotely operated umbilicals are required for truss and berthing connections, but also may be required for manipulator operations. Hence, commonality between end assembly remotely operated umbilicals would be desirable. Umbilicals are classified as tools since they apply push/pull-twist actions and supply (modify) the SSPE to which they attach.

## Tools - Coventional, Standard, and Non-Standard

Requirements taken from PDRD

2.2.4.2.3.4 LEAK DETECTION

A method for detecting, isolating, and repairing leaks within the system shall be provided.

Discussion: This requirement has already been noted in the Sensor End Assemblies area. It is repeated here because it identifies the need for a repair tool.

2.2.4.2.1 REPAIR AND REFURBISHMENT

All radiators shall be designed for degradation limited, on-orbit replacement or refurbishment. The design will utilize heat pipes to allow segmented, replaceable radiator panels.

Discussion: This implies the availability of end assemblies capable of repair operations such as leak sealing, spot welding, etc., and cleaning or recoating operations.

2.2.10.3.1.2 OBSERVATION WINDOWS

Observation windows (excluding hatch through-viewing windows) shall allow adequate space for the operational, maintenance, and recreational tasks by two crewmembers. Laboratory modules shall include optical quality viewing ports. Optical characteristics of all windows shall be maintainable. The transmission of the windows system shall be such as to protect the crew from harmful UV and IR radiation. Means shall be provided to control and minimize the effects of glare, and repair/replace all windows on-orbit.

Discussion: Requires the availability of an end assembly tool (and perhaps a holder) for cleaning and repairing windows.

## Adapters

Requirements taken from PDRD

2.1.2.4.3.1.2 NON-STANDARD TOOLS

Nonstandard tools required for assembly and restoration of payloads shall be provided by the payload (user) organizations; the Space Station shall support user-provided special servicing equipment.

Discussion: Non-standard tools imply an end assembly holder or general purpose adapter to support "user-provided" special servicing equipment that has most of the utilities users are likely to need. This is really an adapter requirement.

Requirements taken from Data Books

The reach envelope of the MSC/MRMS is shown on pages 2A-296, 2A-297, and 2A-299 taken from the data books. (See Appendix A) The upper portion of the solar panels of the Power System lie outside the reach envelop. This implies the need for an extension end assembly (adapter to support inspection and maintenance of the remotely located solar panels.)

## IV. TECHNOLOGY SURVEY

The assessment of the current state-of-art for end effectors was developed by searching out past studies, technical reports and incorporating the current knowledge and awareness of the Working Group Members. A primary source of information was the following Lockheed and Management Services Company (LEMSCO) reports:

1. LEMSCO-20924--"Component Survey for Enhancement of the Shuttle Remote Manipulator System"

2. LEMSCO-21012--"Feasibility Study of Manipulator Terminal Devices for Remote Manipulator System Enhancement"

These reports were prepared in November 1984, for the JSC Engineering Directorate, Systems Engineering Division, under NASA Contract NAS 9-15800, Job Order 53-529. They covered the end effector technology up to the 1984 period.

Although these reports have been updated by Lockheed, these updated versions were not been received in time to include them into this study. Therefore, it was necessary to obtain the information needed by contacting the sources mentioned in the report. Unfortunately, due to the time lag, update information on some of the end effectors was not readily available from the contacts and could not be included into this study. These end assemblies are noted in this report with the recommendation that they be incorporated later when the information becomes available.

A wealth of data was forwarded by the Working Group Members. This information along with the LEMSCO data was reviewed with the intent to limit the end assemblies selected for the data base to those relating to and being considered by NASA for space applications. The purpose was to avoid congestion of the data base with every end assembly on or proposed for the market now. Other end assemblies, such as for industrial applications and medical research, may have potential for space applications and the development of their technology needs to be periodically monitored for future inclusion into the data base.

The end assemblies listed in Table I form the data base for this technology assessment. Figures of these end assemblies are shown in Appendix B. These are the end assemblies contained in or being considered for the Shuttle or Space Station Program. The definition categories that each end assembly fall into are identified. The status of each end assembly is grouped three ways. Those end assemblies that have flown on missions or are capable of becoming flight operational without major rework are classed as "Flight/Protoflight". Those end assemblies that are still in the research stage and exist as engineering lab models are classed as "Eng/Lab." And finally, those end assemblies that are still concepts and have not been developed into significant hardware are classed as "Concepts."

Missing from Table I are several end asssemblies that are related to the robotics area. No identified direct requirements on robotics was found in the data search, other than a requirement to consider its application. Since robotics is being actively researched by all the NASA Centers and is still in its infancy, it is felt that it was too premature to include robotic end effectors at this time. As the research develops an addendum to include robotics could be added to include the following:

1) Dual Arm Manipulator

2) JPL Anthromorphic Hand

3) ERNO Three Multi-Jointed Fingers

4) Utah/MIT Dexterous Hand

5) Standford University Hand

6) MB Associates Dexterous EE

7) Robo-Tech Multiple Prehension Manipulator System (RMPMS)

Also missing from Table I are several end assemblies mentioned in the Lockheed LEMSCO Report for which up-to-date information was missing or very limited. The LEMSCO Report has been updated but was not available to LaRC at the time of this writing. When the report is made available and provides more definition for these end assemblies, this technology assessment could be updated accordingly, to include the following:

1) URI Gripper

2) URI Two-Claw End Effector

3) JPL Prototype End Effector

4) JSC Prototype End Effector

5) ERNO Docking Tool

The following are brief descriptions of the current end assembly technologies partitioned into the SEE and other technology.

## A. The Standard End Effector

Currently only two flight-qualified end assemblies exist: the Manipulator Foot Restraint and the Snare End Effector, now referrred to in NSTS documents as the Standard End Effector (SEE). According to the STS tools document (Catalog No. B1-104, September 1983), the SEE is described as a hollow, light-gauge aluminum cylinder with three wire snares with the ability to capture, release, and rigidize a payload. A schematic of the SEE is shown in Appendix B.1. The captured payload is rigidized when the snare assembly is withdrawn into the end of the end effector, pulling the payload into full contact. The SEE is designed to operate with a Standard Grapple Fixture (SGFO, shown in Figure IV.2), which is designed to be mechanically compatible. Some versions of the SGF have an integrally mounted electrical connector which mates with another connector on the SEE. Thus, the SEE can mechanically and electrically support payload operations. The combination of SEE and SGF has seen considerable use in space and proven to be reliable, effective, and adaptable.

As might be expected, the potential use of the SEE to meet unique Space Station requirements reveals limitations. These inevitable limitations occur when a system is required to perform tasks for which it was not designed. Discussion with NSTS personnel has given both the expected limitations on performance for the SEE and those that appear in operational use. First among the technical limitations are those related to the supply of power through the electrical connector. NSTS can provide up to 1750 W of electrical power at 28 volts DC at Standard Interface Panel in the payload bay. However, the Shuttle Remote Manipulator System/SEE combination can only safely supply around 600 W, a limitation imposed by fuses and the wiring harness on the RMS.

In addition, the SEE undergoes on-orbit degradation that is not well understood, but appears to be related to clutch material modification and reduced lubricant function.

The SEE has a further serious drawback when considered for direct application to the Space Station: It is not interchangeable on-orbit. Lack of on-orbit interchangeability seriously reduces the options available for end assembly redundancy, since the possiblity of several SSPE's having SEE's and sharing them is questionable.

The conclusion to be drawn from the above issues of inadequate power throughput, operational degration of performance, and lack of on-orbit exchangeability, is that the current design for the SEE is not applicable for use on the Space Station.

## B. Other Technology

### Manipulator (Mobile) Foot Restraint (MFR)

The Manipulator Foot Restraint (also designated the Mobile Foot Restraint in the SSP PDRD) is a small work platform attached to the orbiter RMS by means of the standard grapple fixture. It is capable of supporting a crew member and equipment during EVA tasks. The MFR/RMS combination maneuvers the crew member to work sites within reach of the RMS and provides positioning and restraint for accomplishment of the assigned task. The MFR is also a flight qualified end assembly

### Radiator Attachment Mechanism (RAM)

The RAM is being funded under the Shuttle Radiator Assembly Demonstration (SRAD) and will provide means by which the Shuttle RMS can attach and release SRAD radiator elements one at a time. The RAM interfaces with the RMS/SEE by means of a Rigidized Sensing Grapple Fixture (RSGF) and interfaces with the radiator by means of a magnet housed in the RAM. The on/off of the magnet is controlled by the RSGF through a rigidizing/-derigidizing sequence of the RMS/SEE. The radiator element contains a ferrous insert to provide the magnetic connection. Radiator assembly with the RAM provides for an extremely low profile interface fixture on the SRAD radiator elements and permits close assembly of the elements.

This is the only work being done in the program with particular emphasis on assembling radiators. But the RAM could have potential in other areas such as assembly of truss structures and maybe satellite capture by utilizing similar magnetic means.

### JEM/RMS

The JEM/RMS is the SSPE concept being provided by the Japanese. The concept utilizes a SEE and standard grapple fixture that would be common with the SSP/RMS. The systems would be directly interchangeable or indirectly interchangeable through the use of an adapter.

Included in the concept is a small fine arm connected to the main arm snare end effector by the grapple fixture. The small arm is to provide more positioning accuracy for more precise tasks that are not possible with the main arm. The small fine arm concept implies that a small two-finger gripper type end assembly will be utilized for the fine tasks.

Also included in the concept is a tool changer for the small fine arm. A multitude of various type tools can be quick/disconnected to the small fine arm for various assigned tasks.

## ESA Fokker End Effector

ESA is funding a study on End Effector Design with the Dutch firm Fokker. This study proposes a Basic End Effector (BEE) concept with a primary task of grappling and moving an ORU and a secondary funtion of being able to pick up tools for special tasks. The BEE attaches to a specially designed grapple fixture that also may serve as an EVA handle. The purpose of this is to provide compatibility between manipulator and astronaut servicing. However, users of the system would not be compatible with the SSP unless they also provided an SGF. Attached to the exterior of the BEE is the Integrated Service Tool which applies servicing tool torque sized to be compatible with normal astronaut capability, again intended to provide compatibility between manipulator and astronaut servicing.

## Parallel Claw (Two-Finger) Grippers

There are several on-going research programs among the NASA Centers that are looking at Parallel Claw Grippers. These centers are listed below and their grippers:

a) JPL - Smart Hands

b) LaRC - Parallel Two-Jaw Gripper

c) MSFC - Intermesh End Effector

d) MSFC - IOSS Module End Effector

All of these grippers have two simultaneously opening claws of various shapes. The primary activity of these gripper studies is in the area of sensing and controls. Accurate positioning, repeatability, force control, compliances and coordination among multiple components is being evaluated. Secondary activities include looking at various shaped grappling fixtures for handling mechanical devices, structural shapes and tool adapters. The tool adapters will be covered later in this Technology Review.

Smart hands at JPL include the OMV Smart Hand with intermeshing claws capable of sensing force, positions, and rates. Further studies are being made with two laboratory smart hands having force sensing grasping devices other than the intermeshing claw. One is unique in that it utilizes a two-finger grapple with 32-point touch sensors over a 1.5 square inch area to give fine touch sensitivity.

LaRC's Parallel Two-Jaw Gripper is capable of sensing forces, positions and rates. It has an interchangeable set of various shaped claws for various tasks. The primary effort is to develop control programs for Langley's robotic research.

MSFC's Intermesh End Effector is a protoflight end assembly developed for the Protoflight Manipulator Arm (PFMA) and is used to evaluate and demonstrate a set of interchangeable tools. A joint effort between MSFC and JPL is the integration of the intermeshing claw gripper with the smart hand concept.

The MSFC IOSS Module End Effector is a multiple degree of freedom end assembly that interfaces with the modified Module Service Tool (MST) mounted on the Integrated Orbital Service System (IOSS). It can also interface with other modules as well.

Multi-Claw Grippers

In addition to the Parallel Claw Grippers, similar studies are being carried out with Multi-Claw Grippers by NASA Centers:

a) JPL/JSC Multi-Claw Grippers

b) LaRC VersaGrip III

Joint studies between JPL and JSC are being carried out with 3 and 4 claw end assemblies. Again, the primary effort for their studies is in sensing and controls. Motion of the claws is driven by a 4-inch stroke piston which develops a pinching action of the claws to grasp grapple fixtures or objects which are circular, square (for 4-claw configuration), or triangular (for 3-claw configuraton).

Recently, LaRC awarded a contract to Robo-Tech Systems, Worthington, Ohio, to work on "Control Theory and End Effector Laws Using an Advanced Multiple Prehension Manipulator." Robo-Tech will use their VersaGrip III Multiple Prehension Mechanical Hand in this study. Complete force sensing will be added to each of the three fingers and linked to computer control. The Versagrip III is capable of three gripping patterns such as a wrap position (fingers intermesh), three-jaw position (three-fingers meet at tips) and a two-jaw position (two fingers meet at tips). The finger sensor outputs are used to position and determine the gripping pattern. The VersaGrip III will be able to contact an object while adjusting its gripping pattern, to grasp the object or to maintain a controlled prehensile force.

NASA Tool Evaluations

Coordinated with the above gripper studies by the NASA Centers are efforts to integrate tool assemblies with the grippers. These are listed below:

a) LaRC Quick Tool Change Mechanisms

b) MSFC Intermeshing Gripper Tools

c) MSFC Rotary Power Tool

d) MSFC Umbilical Coupling Tool

LaRC is evaluating the tool grasping capabilities of their parallel two jaw gripper. The gripper can handle a ratchet device using manipulator arm wrist motion but the torque is limited with this method. To increase torque capability the two-jaw gripper mechanism was removed and replaced with a rotary torque motor assembly. This system includes a tool rack to hold various quick disconnect tool elements that can be picked up by the torque motor assembly when it inserts a matching quick-disconnect mechanism into the tool.

MSFC is evaluating several tool concepts. Special purpose tools have been made up that can be grasped by the Intermeshing End Effector. The Special Purpose Tool has its own self alignment electrical connector male probe which automatically aligns itself with a matching female electrical connector mounted on the Intermeshing End Effector. Thus, the power required to operate the tool is passed across the interface.

The MSFC Rotary Power Tool was designed to accept different collets for different size and shaped bolt heads. When the manipulator arm with the Intermeshing End Effector grasps the Rotary Power Tool an electrical connector is also mated and the power required to operate the tool is passed across the interface. The amount of torque may be remotely adjusted before the power tool is operated.

The MSFC umbilical coupling tool was made by modifying a Fairchild fluid coupling to mate with the PFMA. The coupling seals on both male and female sides when demated and opens on both sides when mated. The coupling was modified by adding a cylindrical adapter to the female side, guides and a grasping handle to the male side which is grasped by the Intermeshing End Effector. The coupling/decoupling is achieved by remote operation using a hand controller, end effector control and two camera views of the action. Compressed air transferred through the connection demonstrates the mated condition. It is noted that this is the only active umbilical apparatus application study that was uncovered by the Technology Review.

MSFC Inflator End Effector

The MSFC Inflator End Effector was designed to provide one end assembly that is basically independent of configuration shapes. It consists of an expandable bladder with a connector that can be grasped by the Intermeshing End Effector. A self aligning air connector similar to the electrical connector is provided to supply the air required for inflation. Once inserted into a configuration, the inflated bladder takes the configuration shape. Also, a large positioning error is allowable due to the large expansion ratio. This type of end effector would be useful in assembly operations whenever various shaped components are put together.

## Module Service Tool

The Module Service Tool (MST) is a self-contained hand tool for use in installing and removing standard Multimission Modular Spacecraft (MMS) subsystem modules to simplify on-orbit maintenance and repair operations and to reduce the time required for the performance of EVA. The MST is designed to loosen and tighten MMS module fasteners. It provides a means for locking into the modules in a manner which prevents torque backlash on the EVA astronaut.

## Universal Service Tool system (USTS)

The Universal Service Tool System is a concept developed by SPAR to provide various tool systems to be attached to the RMS/SEE. It consists of a grapple fixture adapter with a power drive assembly that accepts various tool assemblies. The concept also has the potential of adapting various types of end assemblies to the RMS/SEE.

## Satellite Retrieval

Capturing and stopping the motions of a satellite tumbling freely along all three axes is a special problem. Several concepts have been brought forth to accomplish these. They are the following:

a) Lockheed AKM Capture Device (ACD)

b) Trunnion Pin Attachment Device

c) Probe Capture Device

(d) Inflatable Capture Devices

(e) Clamping Capture Device

The Lockheed AKM Capture Device (ACD) has been used to capture the Westar Satellite. The ACD is a probe device that is inserted into the rotating axis of the satellite and utilizes friction to slow it down. For the Westar Satellite Operation the major rotation was slowed from Earth. The astronaut using the MMU flew to the satellite and inserted the ACD probe.

The Trunnion Pin Attachment device was developed for the Solar Maximum Repair Mission. It is mounted on the MMU and provides a means for EVA attachment of a grapple fixture to a satellite Trunnion Pin.

The Probe, Inflatable and Clamping capture devices are all concepts that have not been developed. They are all configured with a grapple fixture so that they can be held by the RMS/SEE.

The Probe Capture Device is intended to be inserted into the rotating axis of the satellite and uses retro-actuation (exhaust of $N_2$ tanks) to counteract the rotation of the satellite.

The Inflatable Devices are donut shaped rings that are either slipped over or wrapped around the satellite loosely. Then inflatable rings are expanded to hug and contact the rotating satellite. The inflated rings are free to rotate within the capture device housing until brakes are applied to slow and stop the rotation.

The clamping concepts are devices that open and close around the satellite, and pull it up against friction devices such as brush rollers to slow it down.

MSC Work Station

The MSC is a proposed concept for the Space Station to provide an MRMS Work Platform. Like the MFR, the MSC could attach to the RMS/SEE and provide a foot restraint for the astronaut, but in addition the astronaut would maintain control of the MSC rather than depend on IVA control. The MSC could also have the potential of being the EVA control center for the RMS. Such a system would allow the astronaut to stand back at a safe distance and control the RMS during hazardous operations such as fuel transfers.

# V. COMPARATIVE ASSESSMENT

After the set of requirements has been assembled and the technology has been surveyed, two questions must be answered. First, is there new, fundamental technology that must be worked to enable certain requirements to be met, and secondly, is the technology already in hand adversely affected by unique Space Station system level constraints? The latter question revolves almost exclusively around the major role, clearly evident from the requirements, that the SEE and SGF are expected to play in the Space Station Program.

Therefore, this section has two parts:

A. General Technology vs. Requirements Assessment

B. Standard End Effector--Special Considerations

The final result of this section will be a delineation of the major issues affecting end effectors for Space Station as they appear in the current state of the major program documents and the supporting studies that have been done thus far. The caveat that was noted earlier is worth repeating here: The completeness of the conclusions drawn depend heavily on the uniformity with which the program as a whole is defined and the degree to which that defintion is reflected in the official and supporting documents.

## A. General Technology vs. Requirements Assessment

In figure 1 the results of the matching of basic end assembly technology to straight requirements are shown in matrix form.

Across the top of the matrix are shown, in abbreviated form the types of end assemblies derived from the requirements in Section III. The end assemblies are grouped as Holders, Sensors, Tools, and Adapters. The list along the side represents the available technologies taken from the Technology Survey in Section IV, with only those devices or concepts seriously proposed for space use included.

At the bottom of the matrix is a summary position for each column of requirements. This summary position lists the degree to which the technology is available for use. Presented this way the reader can see at a glance the match between current end assembly technology versus identified requirements.

It should be noted that a blank square implies that within the available technologies considered a currently identified requirement lacks any degree of satisfaction. However, technologies may exist which did not surface in the Technology Survey due to no previously identified application for their development. Therefore, the degree of development necessary to satisfy these requirements is not discernable within the scope of this study.

### Holders

In the area of Holders, (the SEE is also included in the area of holders but will be discussed in detail in a subsequent section) a considerable technology base exists to support the requirements and it is likely that any holder requirement that might occur in the future will have several hardware options from which to draw.

The major issue to be considered comes from the non-SGF fitted elements involved in assembly (also, presumably, in maintenance and operations.) It may be desireable to expect the MRMS/MSC to support assembly in a very direct way. Carrying individual structural elements requires small scale holders, while simply carrying containers of structural elements might require nothing more than the JSC magnetic device.

Size scale is also important in the handling of ORU's. It is clear that small ORU's might benefit from the ESA concept of an EVA compatible grapple fixture, since the SGF may be too large for all exterior mounted ORU's

In the special area of Standard-Grapple-Fixture-compatible holders, a complete technology match exists. The same holds true for end effector support for EVA during intial assembly, in the form of the MFR as far as the requirements are concerned. The requirements are in fact quite specific and the support required is technically unsophisticated. In addtion, Canada is proposing to supply an upgraded version of the MFR, the MSC Work Station, which offers capabilities far beyond that need to meet the requirement (just for intial assembly), and is closer to the earlier proposed OCP.

Sensors

As evident from the matrix, the sensor area is the least matched to the identified requirements. Inspection of Space Station, particularly as the Station grows in complexity, is intuitively a very time-intensive task if done by EVA, particularly injurious to Space Station productivity, and potentially hazardous. The obvious benefit to be derived from remote inspection is firmly in the requirements. The types of inspection might be direct contact or non-contact. The former might be via ultra-sound, surface texture, thermal, vibration, stress and strain, X-rays, magnetic, etc. and the latter might be X-ray stimulated emission, CCD-TV Vision, Gas or Mass Spectrometer leak detectors, laser absorption, IR, radiation, etc.

No end assemblies under development were found whose major purpose was sensing and, in fact, no end assemblies were found that had sensing as a significant minor role other than to support the operation of the end assembly itself. This missing technology area must be considered a major omission on the part of the Space Station Advanced Development Program.

Tools

Two major divisions are evident in Tool end assemblies; those that supply utilities (Umbililicals) and more conventional devices. Umbilicals Requirements have been identified for umbilicals to supply fluids (e. g., cryogens,propulsion, gases), electrical power, and thermal. The operation of the umbilicals is required to be remote in the case of hazardous fluids, and it is likely that requirement would extend to potentially hazardous interconnects of electrical power. Data umbilicals were identified only at the CR level and below, but it is certain that some degree of data communication will be required. For fluids there is a partial match in the MSFC Umbilical Coupling, except for the transfer of cryogens.

Conventional Tools

Conventional tools are needed in the area of leak repair and refurbishment of the TCS Panels and utility runs, which implies some sort of welding, brazing, or sealing tool appropriate to the Ammonia coolant system or heat pipes. There is a partial match here, since the JEM intends to have welding and brazing capability, althought this is concept only. Observation window refurbishment might require some sort of ion-scouring and recoating, or simply a remotely aided window exchange technique with internal cleaning and refurbishment. There is no identified tool for this activity, and the requirement is not that clear-cut.

Adapters

One important requirement that has been identified here is that the Space Station Program has committed itself to support user supplied servicing tools. Such a committment is a fairly broad one, undertaking to support whatever (it is assumed within reason) user service equipment the user is prepared to supply. At the very least, this is a requirement for adapters to connect user service tools to Space Station Elements involved in servicing user payloads: Service Bay and MRMS/MSC.

In fact this requirement extends to the Telerobotic Servicer, and affects the OMV as carrier. A large number of the holders are partially able to support user service tools, but since this area is still wide open, only definition of policy can yield better assessment.

## B. Standard End Effector--Special Considerations

As can be seen from the Technology vs. Requirements Matrix, the Standard End Effector (SEE) is capable of meeting all requirements directly associated with the use of the SGF. User payloads, Modules, STS interfaces, ORU carriers, Service Bay, visiting space craft, etc. all are either clearly identified as having, or expected to have, the SGF as the electromechanical interface. No other reference to end assembly interfaces approaches those related to the SGF. By inference, the SEE is far and away the most likely mate to the SGF. Historical precedent, flight experience, and design are all strong reasons for this association. Without a doubt the application of the SEE to operations requiring manipulation (and some holding operations) is the leading candidate.

The application of the SEE to the Space Station environment, however, is not straight-forward. Certain operational constraints exist which have an important bearing on the direct application of the SEE to Space Station requirements. The NSTS environment differs operationally in many respects, but two are important here: limited in-space use for NSTS hardware and lack of requirement for on-orbit maintainability for NSTS. Discussions with NSTS personnel or individuals closely associated with the development and use of the SEE have provided information concerning the existence of degradation mechanisms in the SEE. The exact cause of the degradation is not known, but two informed views have been advanced. Either exposure to vacuum or opening/closing cycles (rigidization cycles) lead to reduction in SEE performance. After about 400 to 500 rigidization cycles (one view) or a couple weeks space exposure (another view) the SEE is strongly considered for return to SPAR for tear-down/ refurbishment. Thus, the SEE, as currently built undergoes a progressive degradation requiring refurbishment to maintain a significant confidence level in its ability to perform reliably.

The second point concerns maintainablility. The SEE is attached to the wrist of the RMS and is covered with a thermal protection coat. The SEE is attached by several bolts, some of which are "hidden," through the wrist joint and threaded into the SEE back plate. In addition connectors and grounding straps are provided which are not designed for quick disconnect. Thus, the SEE is not on-orbit maintainable at any level.

The implications for the Space Station are important. The assembly sequences for the Space Station involve early involvement of Shuttle RMS/SEE (no problem here) transferring at an early flight (2-3) to support from the MRMS/MSC. Once in space, an SEE on the MRMS would be exposed to vacuum for an indefinite time. On the other hand the number of cycles the SEE would go through are significant. An estimate of the number of cycles for the SEE during assembly has been estimated from the 14 STS-Flight Baseline Assembly Sequence. The number of rigidization cycles is estimated from the list in figure 2 to be 443. Moreover, assuming the rate of 2.5 cycles per EVA hour and using the Rockwell Work Package-2 estimate of 685 EVA maintenance hours during assembly from figure 3, yields an additional 3424 rigidization cycles (two maintenance rigidization cycles to repair one assembly cycle.) Thus, a total of nearly 4000 cycles will be required during the assembly sequence. Whereas these numbers are obviously subject to considerable modification, the message is clear: either because of time or cycles, the SEE would be very much in need of refurbishment or repair during the assembly sequence.

The conclusion is difficult to avoid that the current Standard End Effector is inadequate to do the job planned for it on the Space Station.

## C. Comparative Assessment Summary

From this comparative assessment, a few major conclusions can be drawn. These conclusions relate to both the applicability of the current SEE to the Space Station Program and to the need for new end assembly technology to meet Space Station requirements.

1. There are no Flight-Qualified End Effectors, including the SPAR snare end effector, capable of meeting Space Station requirements.

2. With regard to assembly in general, only the manipulator foot restraint can meet Space Station requirements.

3. In the area of tool end assemblies, only umbilicals appear to be in an advanced stage of engineering development, but are restricted to non-cryogenic gases and fluids.

4. A partial data or electrical power transfer capability exists in the SEE, although it is inadequate to meet current Space Station requirements for payload power support.

5. There is a complete lack of development for sensor end assemblies, but there exists clear Space Station requirements for them.

6. In general, there is a tremendous technology in holders from which the Space Station Program can draw.

7. Whereas there is only CR-level support for an EVA compatible ORU handling fixture and none for an EVA-suited-hand compatible end assembly, an EVA-sized end assembly and ORU handling fixture seem very desireable.

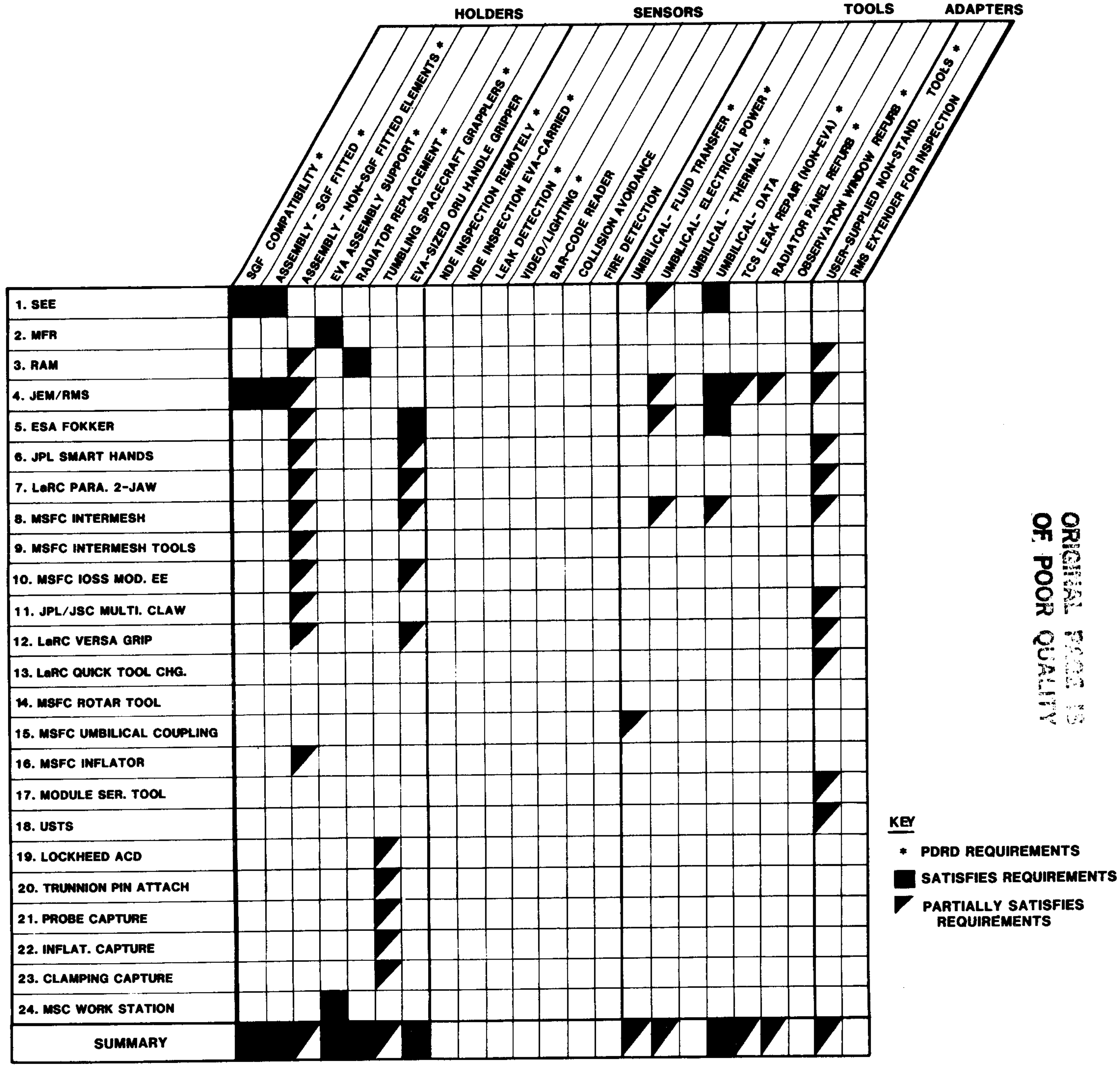



Figure 1 - COMPARATIVE ASSESSMENT MATRIX--TECHNOLOGY vs. REQUIREMENTS

# VI. END ASSEMBLY STRATEGIES

## Requirements

A. Advanced development is required to meet end assembly requirements for the following:

1. Cryogenic Umbilicals
2. Hazardous Fluid Umbilicals
3. Sensor Assemblies
4. TCS Umbilicals

B. Upgrade power tranfer capacity

## Redesign or Modification Options

Options involving redesign or modification required for improved reliability and maintainability are listed below:

A. Develop Standard End Assembly (SEA)
   1. Extended mean-time between failures (10-20 years)
   2. On-orbit removable with moderate MTBF (1-5 years)
   3. Make on-orbit quick disconnectable with increased MTBF over SEE
      a. Spares inventory
      b. Interchangeable/compatible
         (1) SSPE
         (2) SSPE and NSTS
      c. IVA Repairable
   4. Make on-orbit, in situ, repairable

B. Modify Standard End Effector (SEE) for On-Orbit Replacement
   1. Spares inventory
   2. Interchangeable/compatible
      a. SSPE
      b. SSPE and NSTS

## Implementation Options

Options for implementing are the following:

A. Make all end assemblies compound.

B. Make some end assemblies compound and some simple depending upon required service.

## Recommendations

A quantitative recommendation for a total policy with regard to an "End Effector Strategy" for the Space Station Program would require the creation of objective criteria, the development of a generalized "cost benefit" analysis, and an application of those metrics to the various major options to determine the "best." However, an heuristic approach is possible as a result of the very obvious central role that the Standard End Effector must play and its very obvious lackings vis a vis a Space Station role.

As a central theme any options analysis must address the Standard End Effector-related issues identified in this study. It is furthermore clear that there are some very important end assemblies, impled or explicitly stated, contained in the requirements that are completely unaddressed by the current content of the Advanced Development Program, within sensible reach through Focused Technology and its relatives in Code R, or for that matter, in company related IR&D.

It is also clear that compatibility of ORU handlng via the Standard Grapple Fixture is an attractive capability that might be required for at least some End Assemblies associated with large manipulators. Moreover, since compatibility opens the door to considering interchangeability, requiring commonality for some End Assemblies offers major advantages with regards to sparing.

Interchangeability implies the ability to replace End Assemblies on-orbit and, if on-orbit replacement is possible, non-standard End Assemblies are also supportable.

Finally, if the interface and upgrade problems are technically tractable, it would also be desirable to upgrade the NSTS Standard End Effector to modern SSP technical standards, including interchangeability.

For the foregoing, admittedly heuristic, reasons a recommendation at this point would be that (1) missing technology development in Sensor End Assemblies, Umbilicals, and a new, EVA compatible, Grapple Fixture be immediately addressed, (2) that the SEE be upgraded in both reliability, utility support, etc., (becoming the Standard End Assembly, SEA) and made on-orbit replaceable, (3) that all SSPE's expecting logistics support and possessing a large-scale logistics support manipulator be required to have at least one common/interchangeable, new SEA. Further simplification and over-all system capability enhancement would come from (4) simultaneous upgrade of the NSTS RMS/SEE to commonality with SEA. Finally (5), all End Assemblies would then be made compound or simple, depending on the best design solution to a particular task.

## Follow-On Activity

Several areas have been identified that merit further consideration: A continuing study activity to further identify requirements that either specifically call for or imply end assemblies, to develop quantitative methodologies for selecting the best program policies in commonality, interchangeability, etc., to continue to identify and address technology issues, and to grow into a self-consistent program policy with respect to End Effectors.

It is clear that a major activity is needed to address the issue of upgrading or redesigning the current NSTS Standard End Effector and the degree to which a Space Station Standard End Assembly can be levied on all Space Station participants; International as well as U.S.

In addition, work on certain specific End Assemblies is clearly called for. Work is needed in extending umbilicals to the transfer of cryogenics, heating and cooling, hazardous fluids, and power. At least a study activity in developing a new EVA compatible small standard grapple for ORU's as suggested by ESA is in order. Last, but not least, definition and Advanced Development is clearly mandated for Sensor End Assemblies by the mismatch between strong PDRD requirement and lack of Space Station or other activity in this area.

TABLE I

| ITEM | DESCRIPTION | DEFINITION CATEGORY | FLT/PROTO FLT | ENG/LAB | CONCEPT |
|---|---|---|---|---|---|
| 1. | STANDARD END EFFECTOR (SEE) | HOLDER | X | | |
| 2. | MANIPULATOR FOOT RESTRAINT (MFR) | HOLDER | X | | |
| 3. | JSC MAGNETIC RAM | HOLDER | X | | |
| 4. | JEM/RMS STANDARD END EFFECTOR | HOLDER | | X | |
| | A. JEM/RMS FINE ARM | COMPLEX | | X | |
| | B. JEM/RMS TOOL ASSEMBLY | TOOL | | | X |
| 5. | ESA FOKKER END EFFECTOR | HOLDER | | X | |
| | A. ESA TOOL ASSEMBLY | TOOL | | X | |
| 6. | PARALLEL CLAW GRIPPERS | | | | |
| | A. JPL OMV SMART HAND | HOLDER | | X | |
| | B. LARC PARALLEL TWO JAW GRIPPER | HOLDER | | X | |
| | C. MSFC INTERMESH END EFFECTOR | HOLDER | | X | |
| | D. MSFC IOSS MODULE END EFFECTOR | HOLDER | | X | |
| 7. | MULTI-CLAW GRIPPERS | | | | |
| | A. JPL/JSC MULTI CLAW GRIPPERS | HOLDER | | X | |
| | B. LARC VERSAGRIP III | HOLDER | | X | |

TABLE I (cont)

| ITEM | DESCRIPTION | DEFINITION CATEGORY | FLT/PROTO FLT | ENG/LAB | CONCEPT |
|---|---|---|---|---|---|
| 8. | NASA TOOL EVALUATION | | | | |
| | A. LARC QUICK TOOL CHANGE MECHANISM | TOOL | | X | |
| | B. MSFC INTERMESHING GRIPPER TOOLS | TOOL | | X | |
| | C. MSFC ROTARY POWER TOOL | TOOL | | X | |
| | D. MSFC UMBILICAL COUPLING | TOOL | | X | |
| 9. | MSFC INFLATOR END EFFECTOR | HOLDER | | X | |
| 10. | MODULE SERVICE TOOL | TOOL | X | | |
| 11. | UNIVERSAL SERVICE TOOL SYSTEM | TOOL | | X | |
| 12. | SATELLITE RETRIVAL | | | | |
| | A. LOCKHEED AKM CAPTURE DEVICE | HOLDER | X | | |
| | B. TRUNNION PIN CAPTURE DEVICE | HOLDER | X | | |
| | C. PROBE CAPTURE DEVICES | HOLDER | | | X |
| | D. INFLATIBLE CAPTURE DEVICES | HOLDER | | | X |
| | E. CLAMPING CAPTURE DEVICES | HOLDER | | | X |
| 13. | MSC WORK STATION | COMPOUND | | | X |

| FLIGHT NO. | EVA NO. | EVA MIN. | NO. SEE CYCLES[b] |
|---|---|---|---|
| 1 | 1 | 350 | 17 |
| | 2 | 332 | 23 |
| | 3 | 305 | 15 |
| 2 | 1 | 328 | 13 |
| | 2 | 350 | 11 |
| | 3 | 337 | 32 |
| | 4 | 330 | 16 |
| 3 | 1 | 329 | 13 |
| | 2 | 329 | 14 |
| | 3 | 345 | 10 |
| | 4 | 342 | 6 |
| 4 | 1 | 344 | 15 |
| | 2 | 344 | 15 |
| | 3 | 315 | 6 |
| | 4 | 190 | 15 |
| 5 | 1 | 355 | 13 |
| | 2 | 361 | 10 |
| | 3 | 361 | 10 |
| | 4 | 255 | 6 |
| 6 | 1 | 307 | 13 |
| | 2 | 335 | 11 |
| | 3 | 335 | 11 |
| | 4 | 350 | 10 |
| 7 | 1 | 310 | 26 |
| | 2 | 345 | 10 |
| | 3 | 345 | 10 |
| | 4 | 275 | 8 |
| 8 | 1 | 332 | 14 |
| | 2 | 335 | 8 |
| | 3 | 325 | 9 |
| 9 | 1 | 60 | 1 |
| 10 | 1 | 60 | 1 |
| 11 | 1 | 250 | 8 |
| 12 | 1 | 97 | 9 |
| 13 | 1 | 165 | 4 |
| | | 180 TOTAL EVA HOURS[c] | 443 TOTAL CYCLES |

Figure 2. Top Level EVA Timelines and SEE Cycles for Baseline Assembly Sequence[a]

a. From R. H. Waibel, personal communications, McDonnel Douglas, Houston, Texas, March 1986.

b. 2.5 SEE Cycle per EVA hour

c. 180 total EVA hours equals 360 total EVA manhours

| FLIGHT NO. | EVA MANHRS (CORRECTIVE) | EVA MANHRS (OVERHEAD) | EVA MANHRS (RESOURCES & TRAVEL) | IVA MANHRS (CORRECTIVE) | TOTAL BY FLIGHT NO. |
|---|---|---|---|---|---|
| 1 | 7.5 | 11 | 2 | ----- | 20.5 |
| 2 | 11.7 | 11 | 2 | ----- | 24.7 |
| 3 | 15.7 | 22 | 4 | ----- | 41.7 |
| 4 | 19.3 | 22 | 4 | ----- | 45.3 |
| 5 | 21.3 | 22 | 4 | ----- | 47.3 |
| 6 | 24.9 | 22 | 4 | ----- | 50.9 |
| 7 | 27.3 | 33 | 6 | ----- | 66.3 |
| 8 | 30.1 | 33 | 6 | ----- | 69.1 |
| 9 | 27.1 | 33 | 6 | 0.8 | 66.9 |
| 10 | 24.1 | 22 | 4 | 1.6 | 51.7 |
| 11 | 21.7 | 22 | 4 | 2 | 49.7 |
| 12 | 21.5 | 22 | 4 | 2.5 | 50 |
| 13 | 22.3 | 22 | 4 | 2.9 | 51.2 |
| 14 | 20.5 | 22 | 4 | 3.2 | 49.7 |
| TOTALS | 295 | 319 | 58 | 13 | 685 |

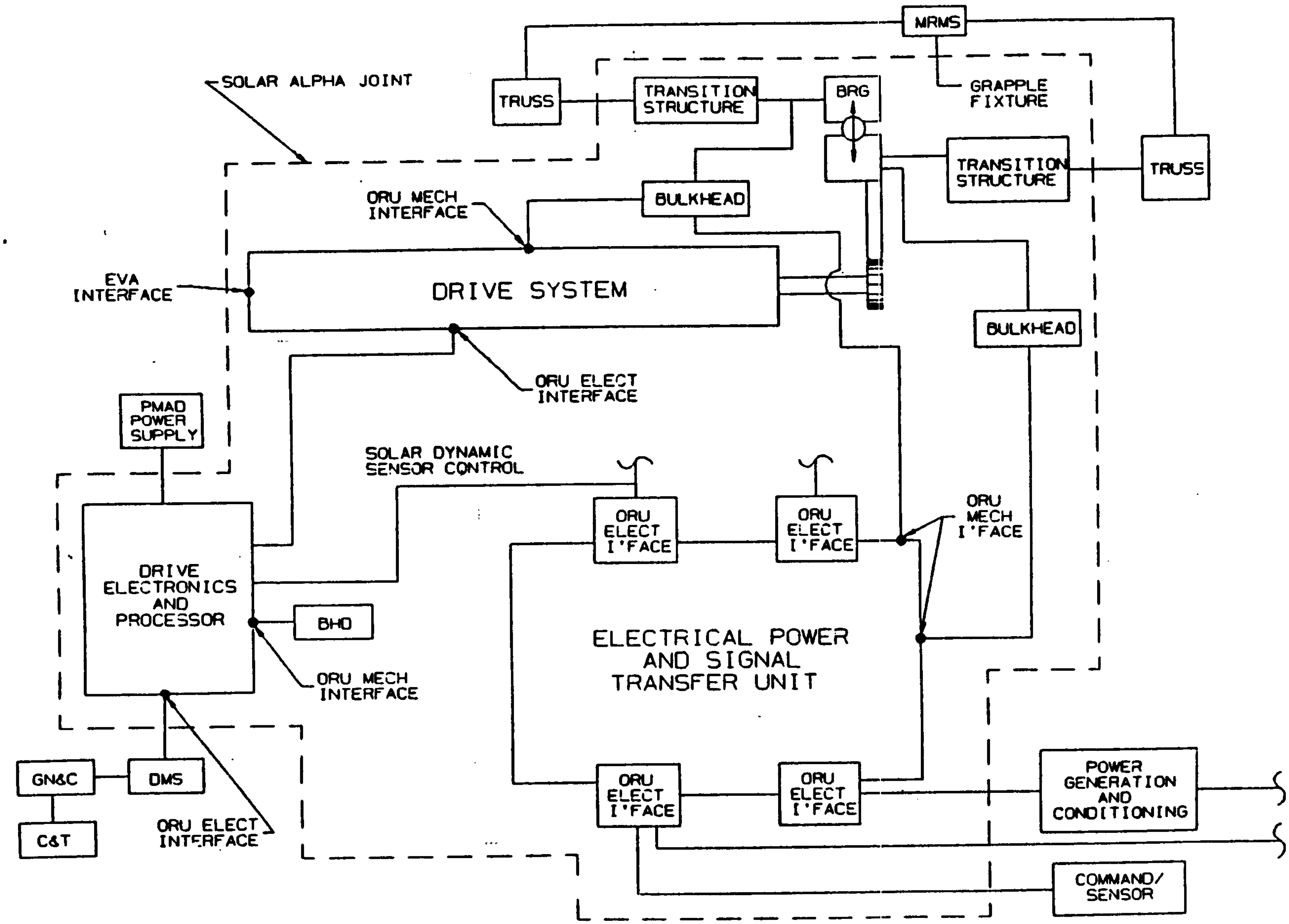
FIGURE 3 - MULTIPLE EVA TASKS ACCOMPLISHED ON A SINGLE EVA EXCURSION
(SIX PRODUCTIVE EVA HOURS PER MAN)

# APPENDIX A

## DATA BOOK FIGURES

FIGURE 4

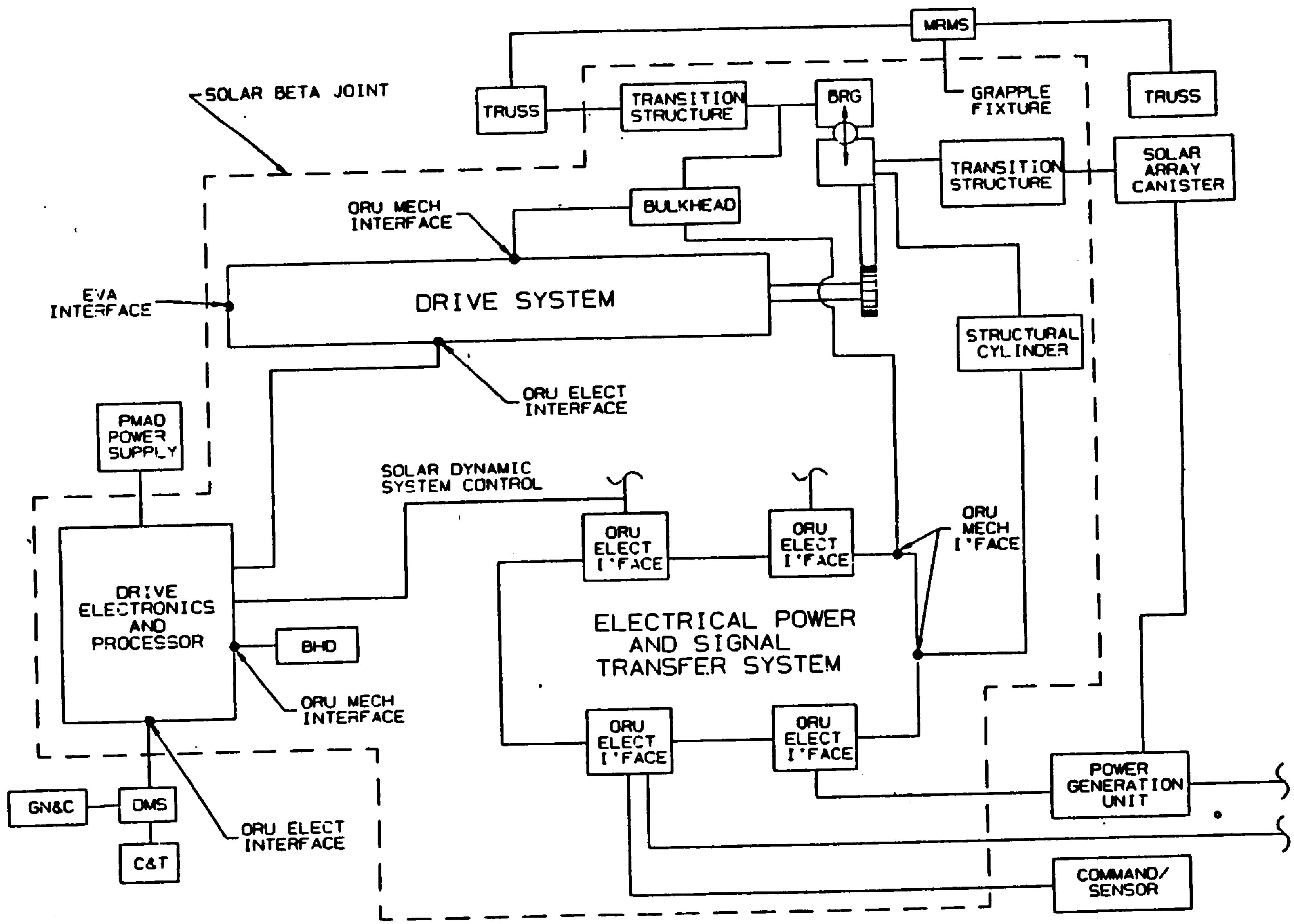
# Hardware Schematic Solar Alpha Joint




16SSS174556

FIGURE 6

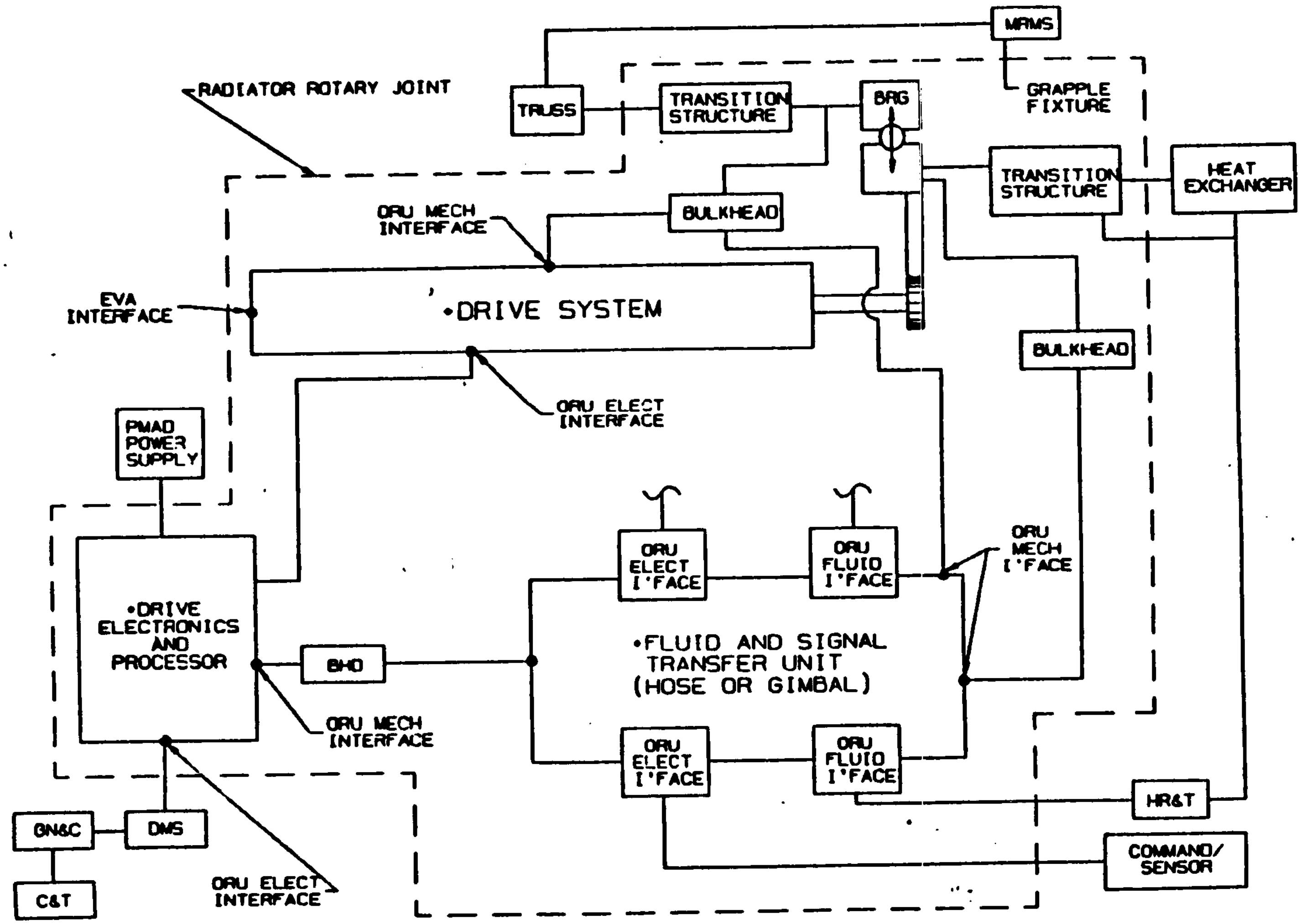
# Hardware Schematic Solar Beta Joint




16SSS174557

FIGURE 8

# Hardware Schematic Radiator Rotary Joint

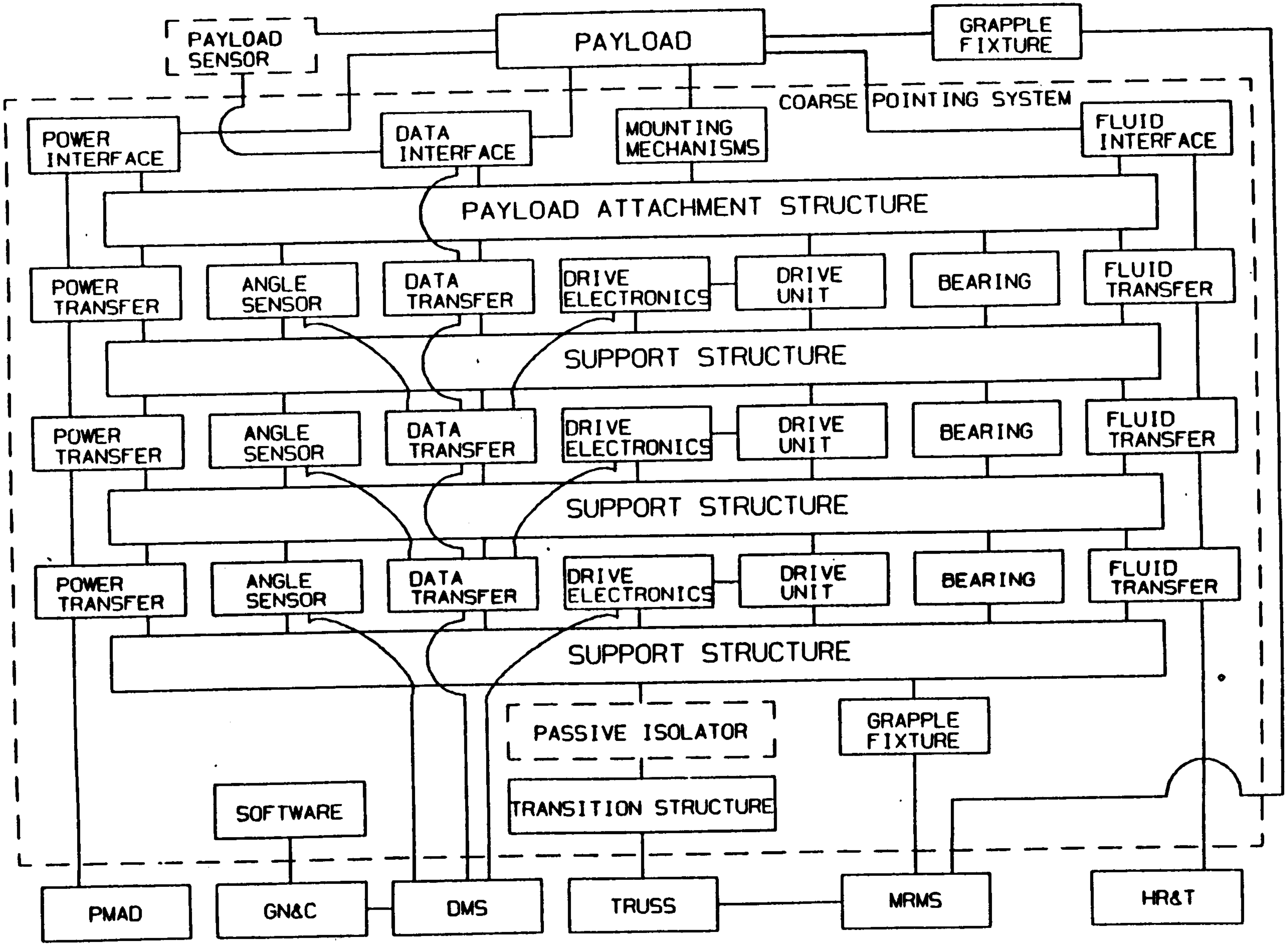



•REDUNDANT (SINGLE FAULT TOLERANT)

16SSS174558

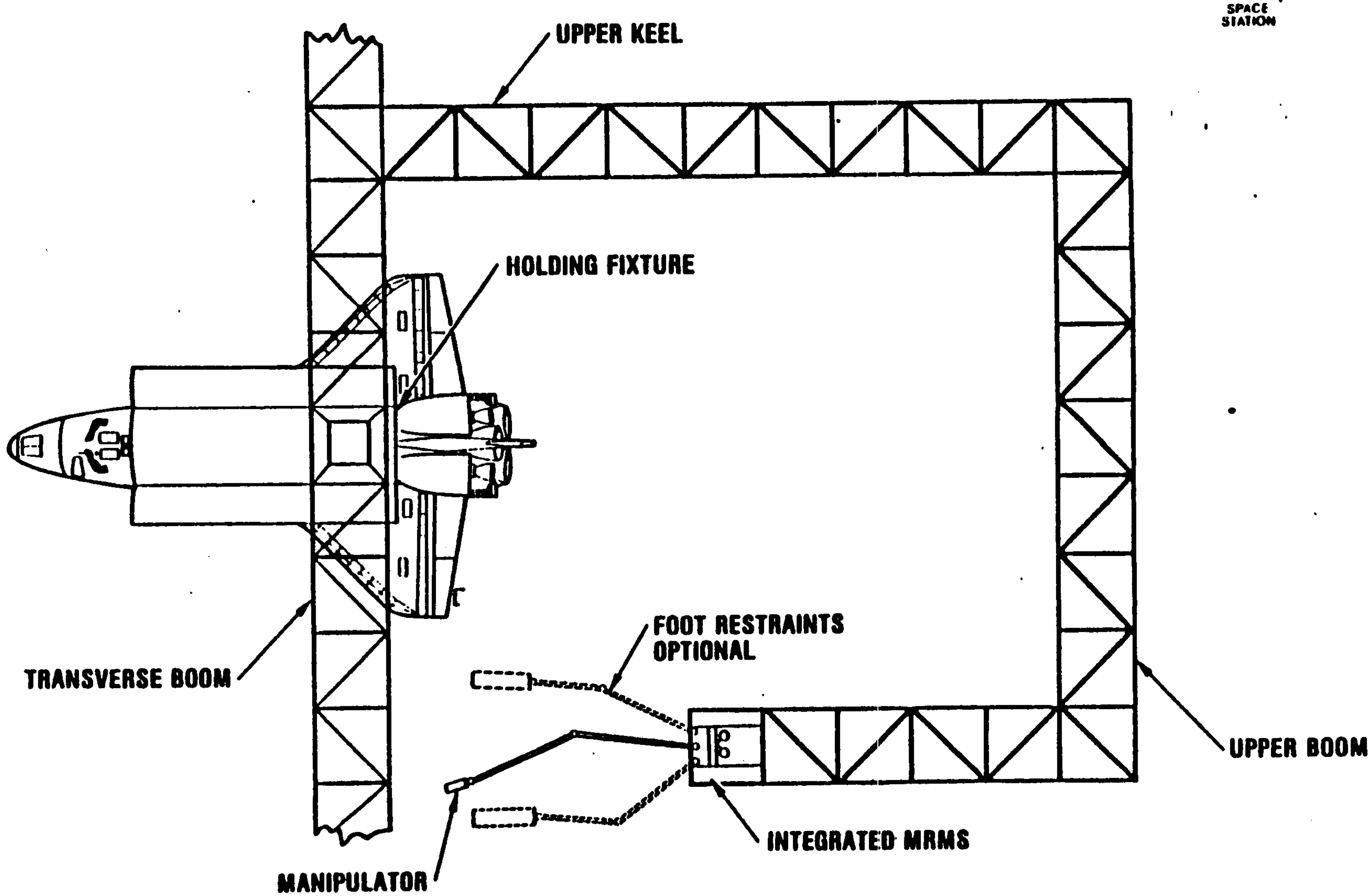
FIGURE 12

# CPS Hardware Schematic




16SSS174546

# Integrated MRMS Used fc Sequential Bay Assembly for Launch No. 3 Assembly Operations



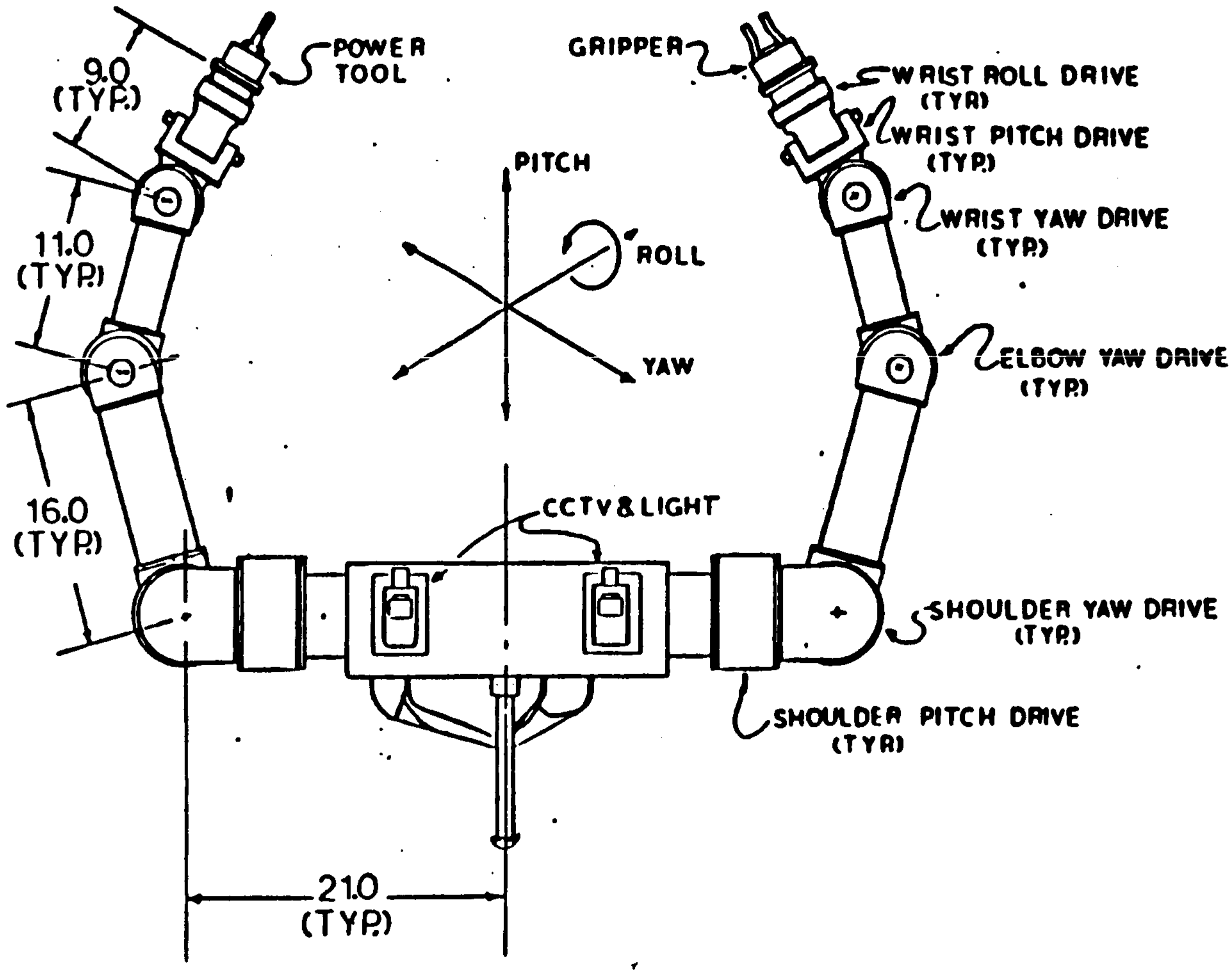

Rockwell International
Space Station Systems Division

22

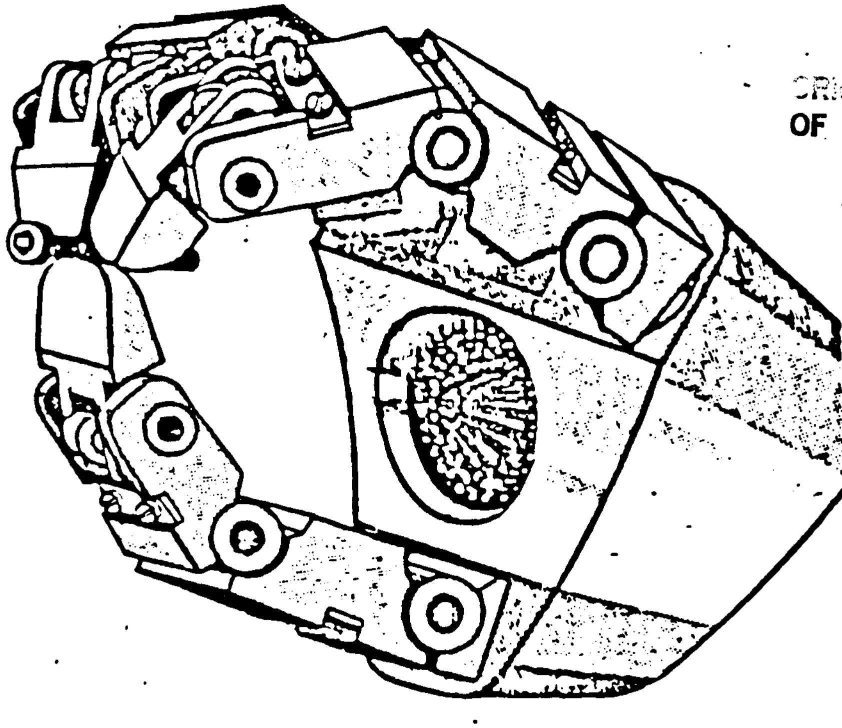
16SSS174674A

# APPENDIX B

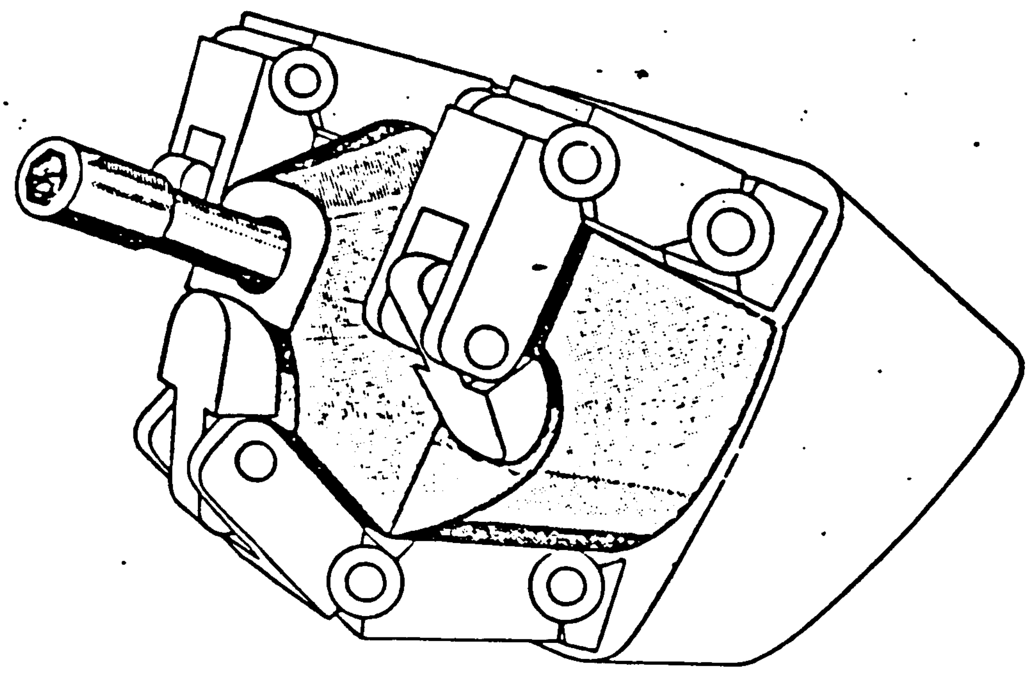
## PICTURES AND FIGURES OF REVIEWED END ASSEMBLIES




DUAL ARM END EFFECTOR

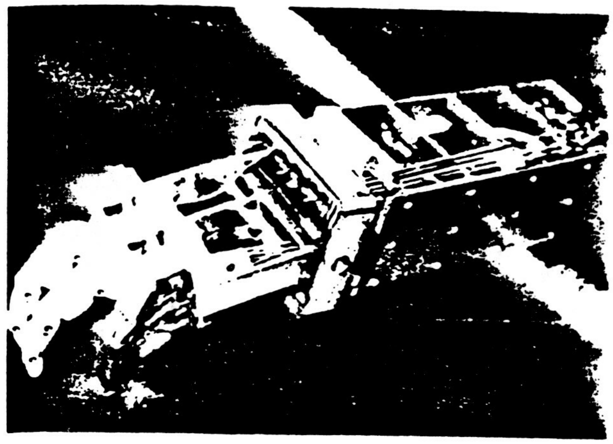


Three finger hand

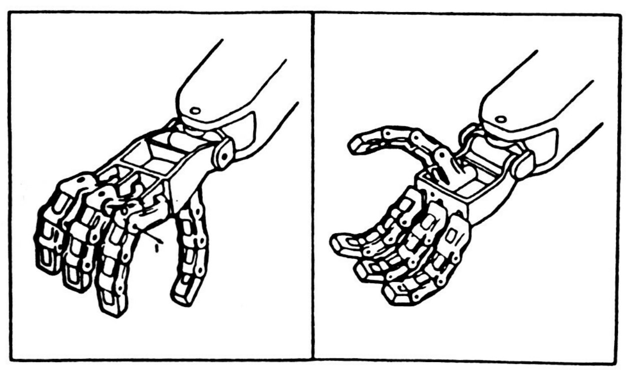


Tool with a three-finger-adapter

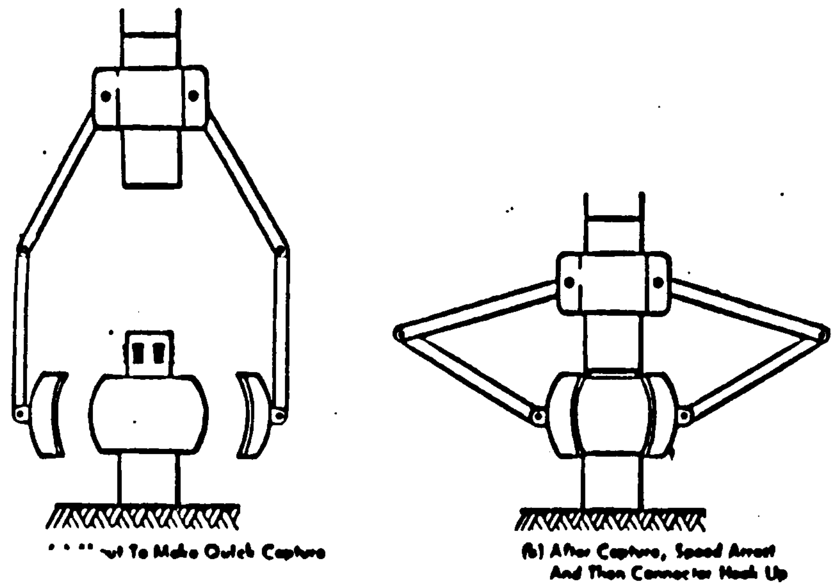
3-MULTI-JOINTED FINGERS EFFECTOR
(ERNO RAUMFAHRTTECHNIK GMBH)



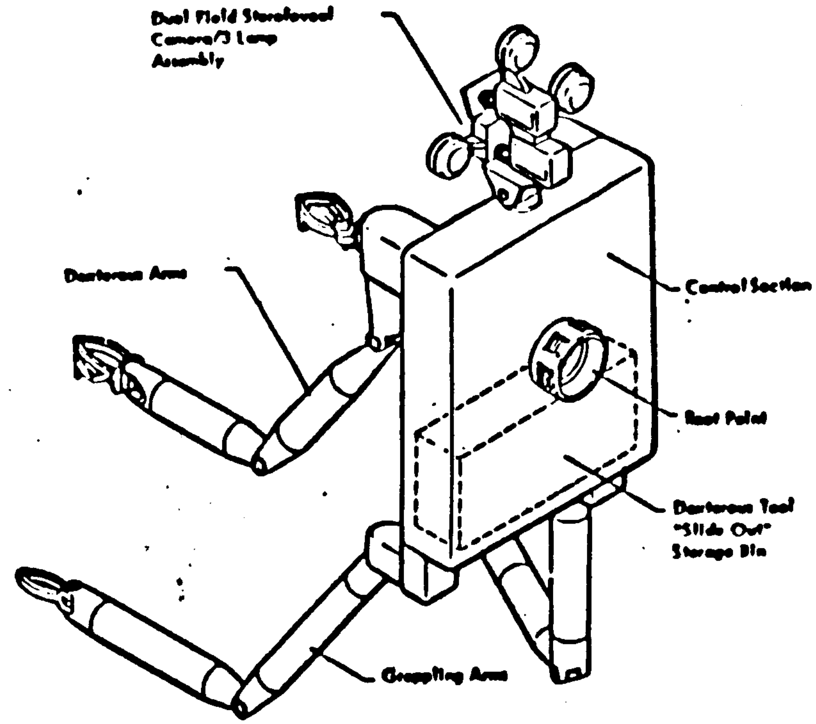
The prototype Version I DH.



Utah/MIT DH. Note the separation between the 0 and 1 joint axes of each digit.

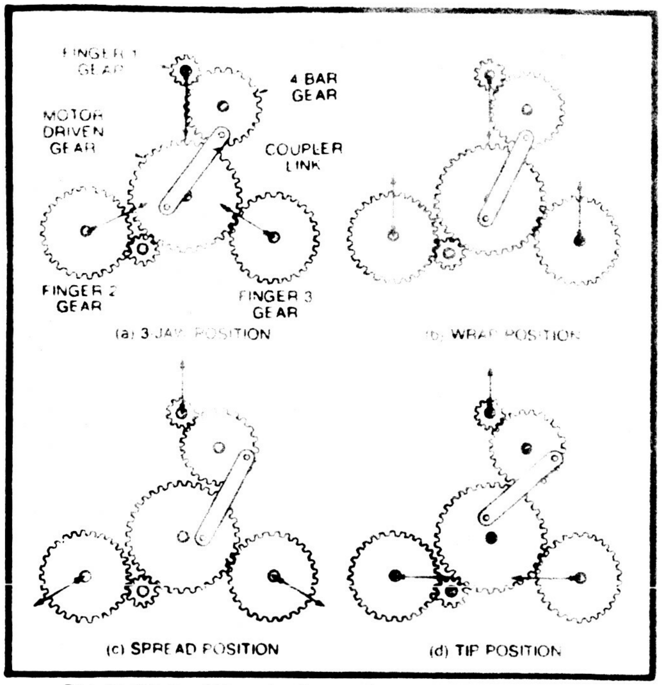



SCHEMATIC SHUTTLE CAPTURE QUICK GRASP END EFFECTOR

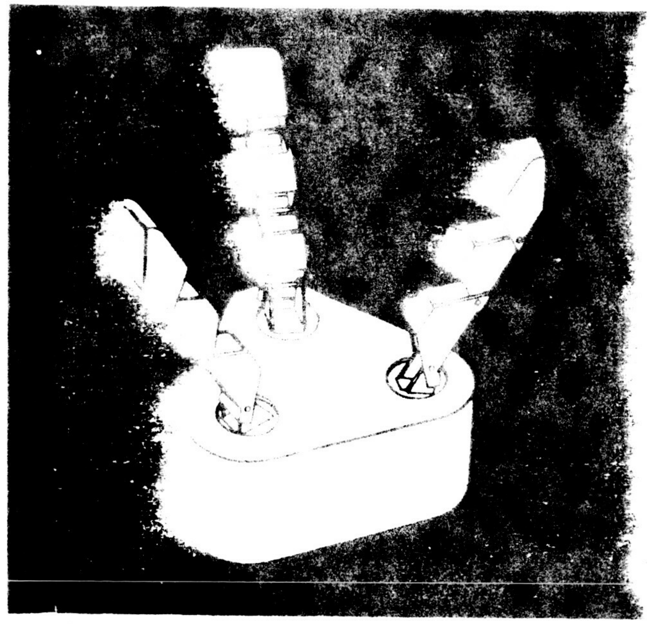



SCHEMATIC DEXTEROUS END EFFECTOR

# MB ASSOCIATES EE CONCEPTS

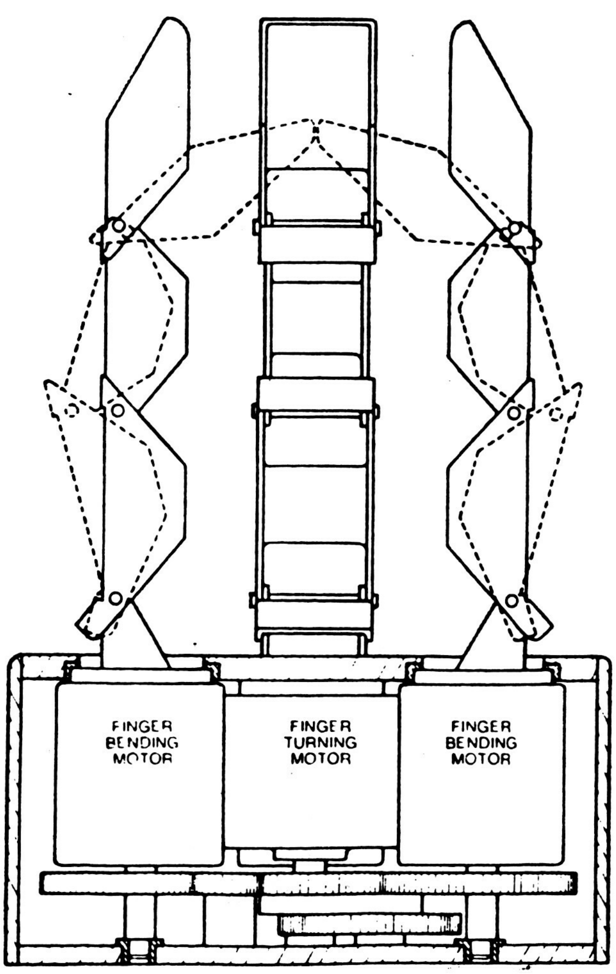


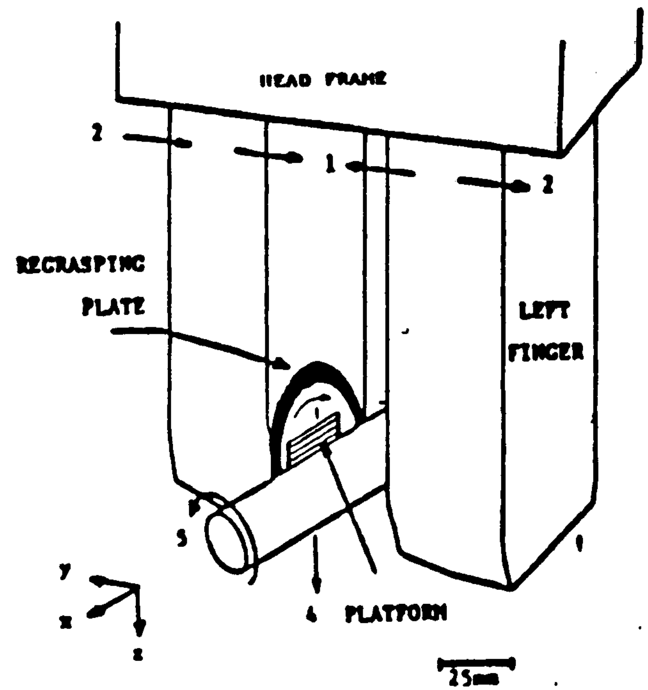

The double-dwell finger turning mechanism.



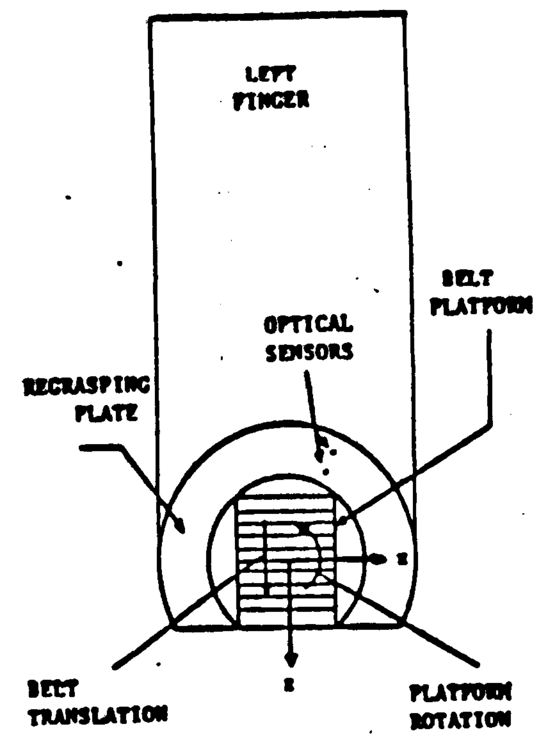
A sketch of the MPSMS hand built for NASA

MPMS hand with a double-dwell mechanism located in its base



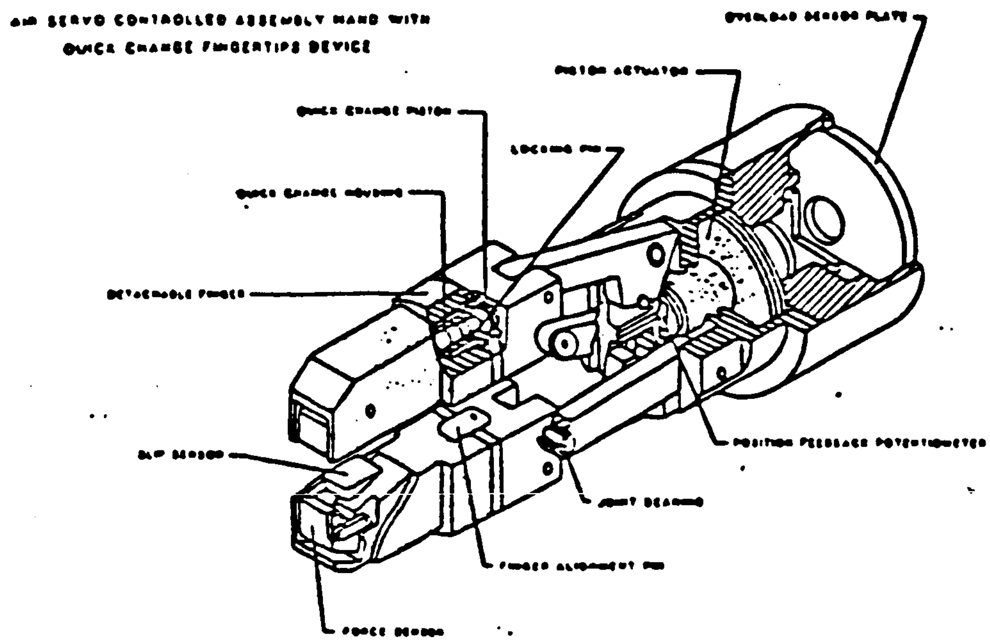


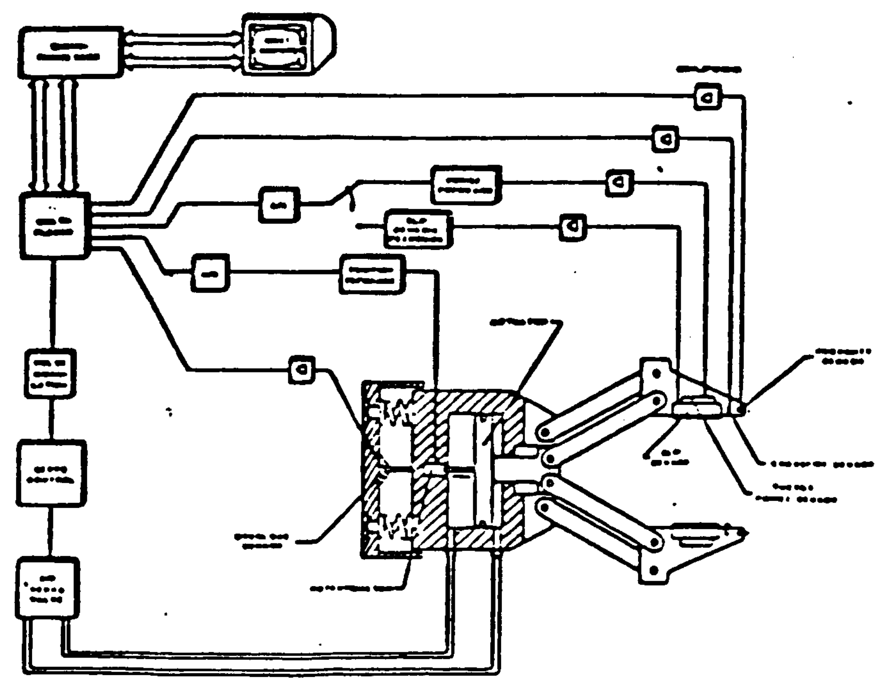

Representation of the hand's motions with a cylindrical workpiece.



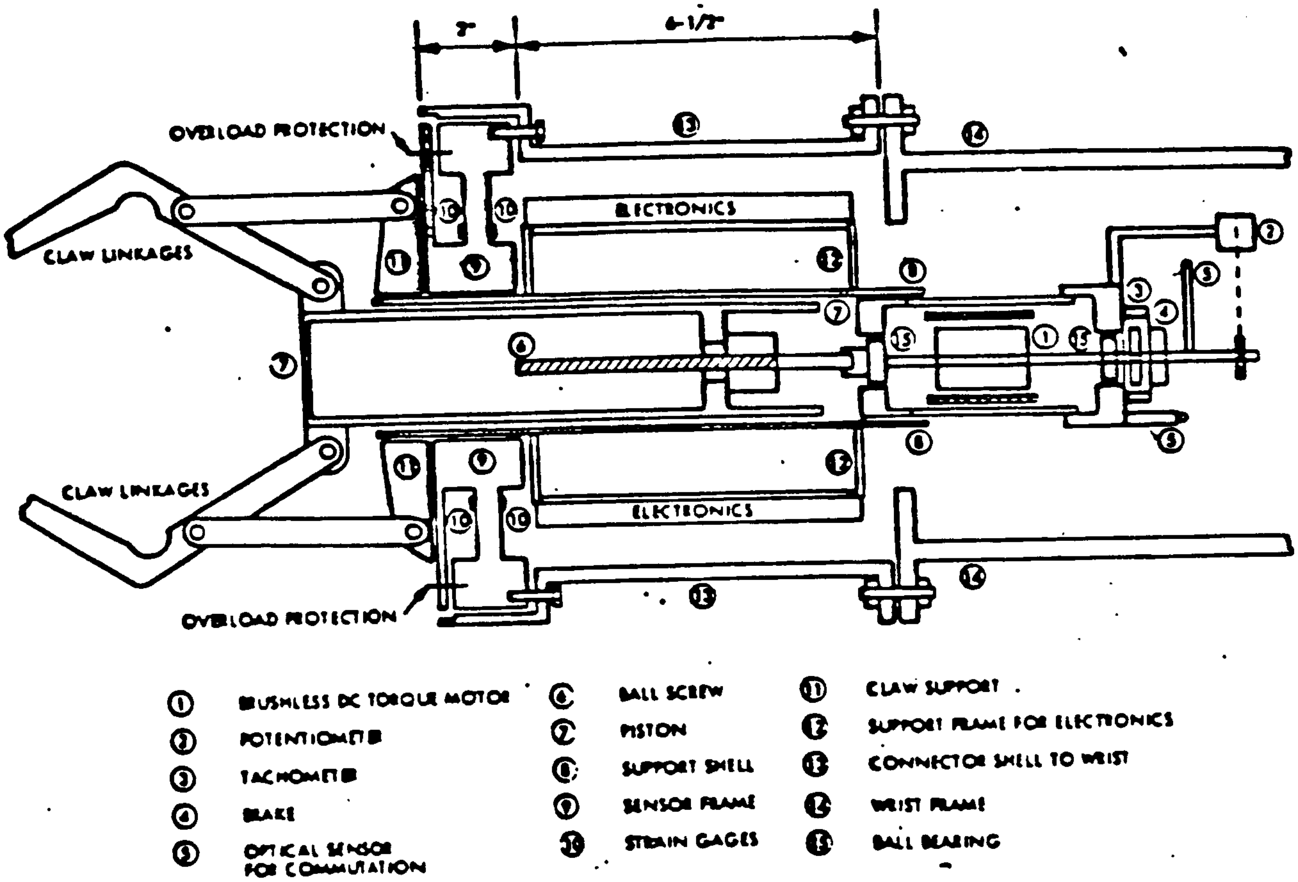

Finger configuration.

URI GRIPPER (EE)



URI-END EFFECTOR




JPL-PROTOTYPE END EFFECTOR

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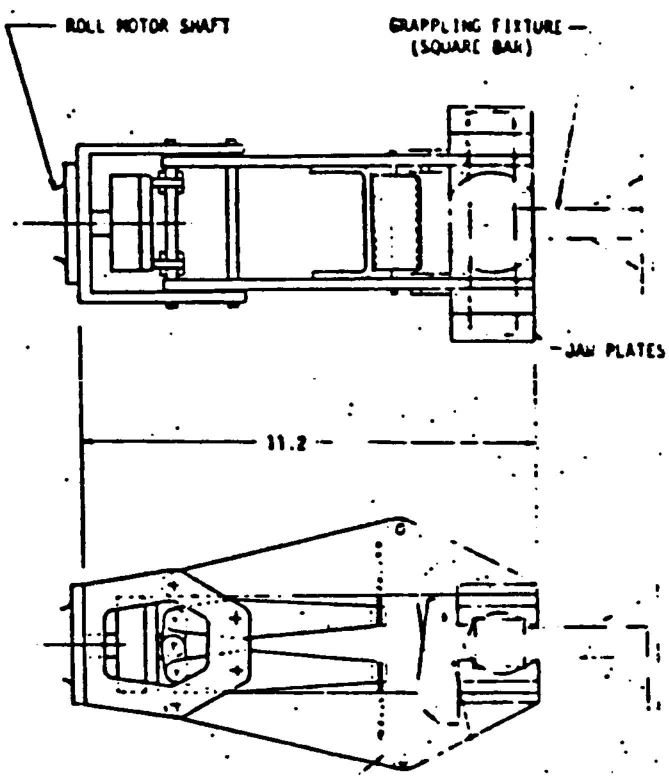
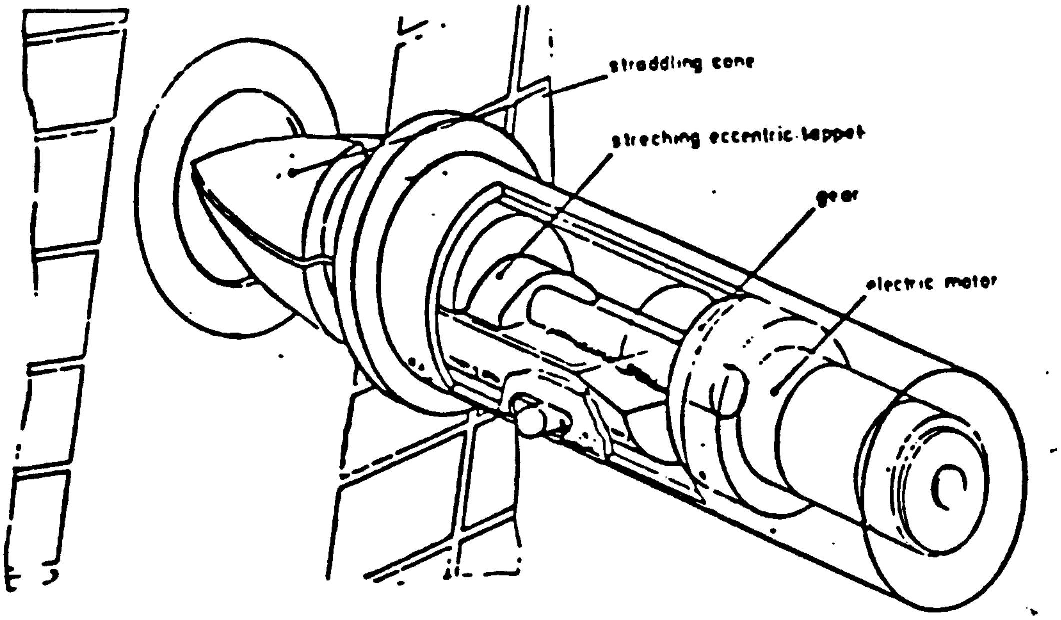
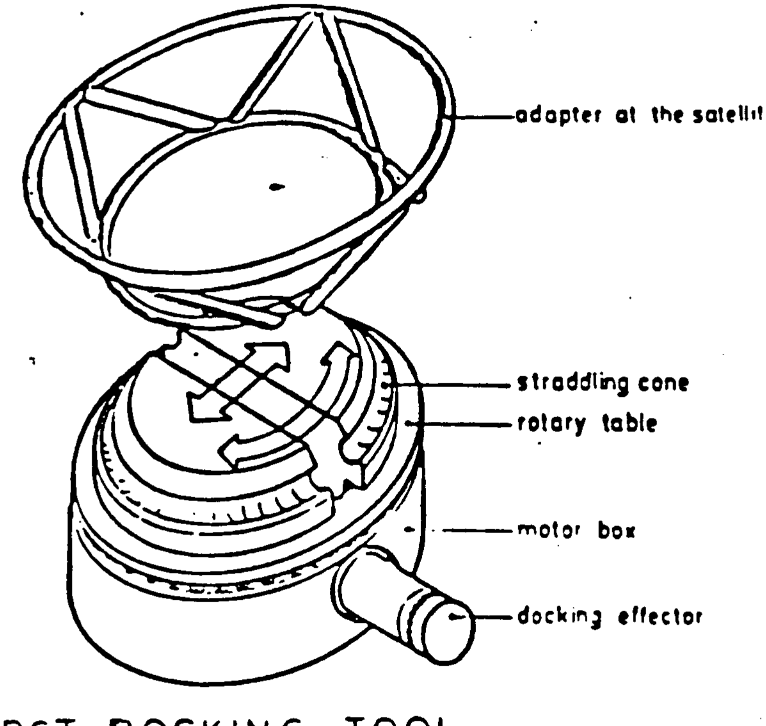



END EFFECTOR CONFIGURATION III/IV

JSC PROTOTYPE END EFFECTOR

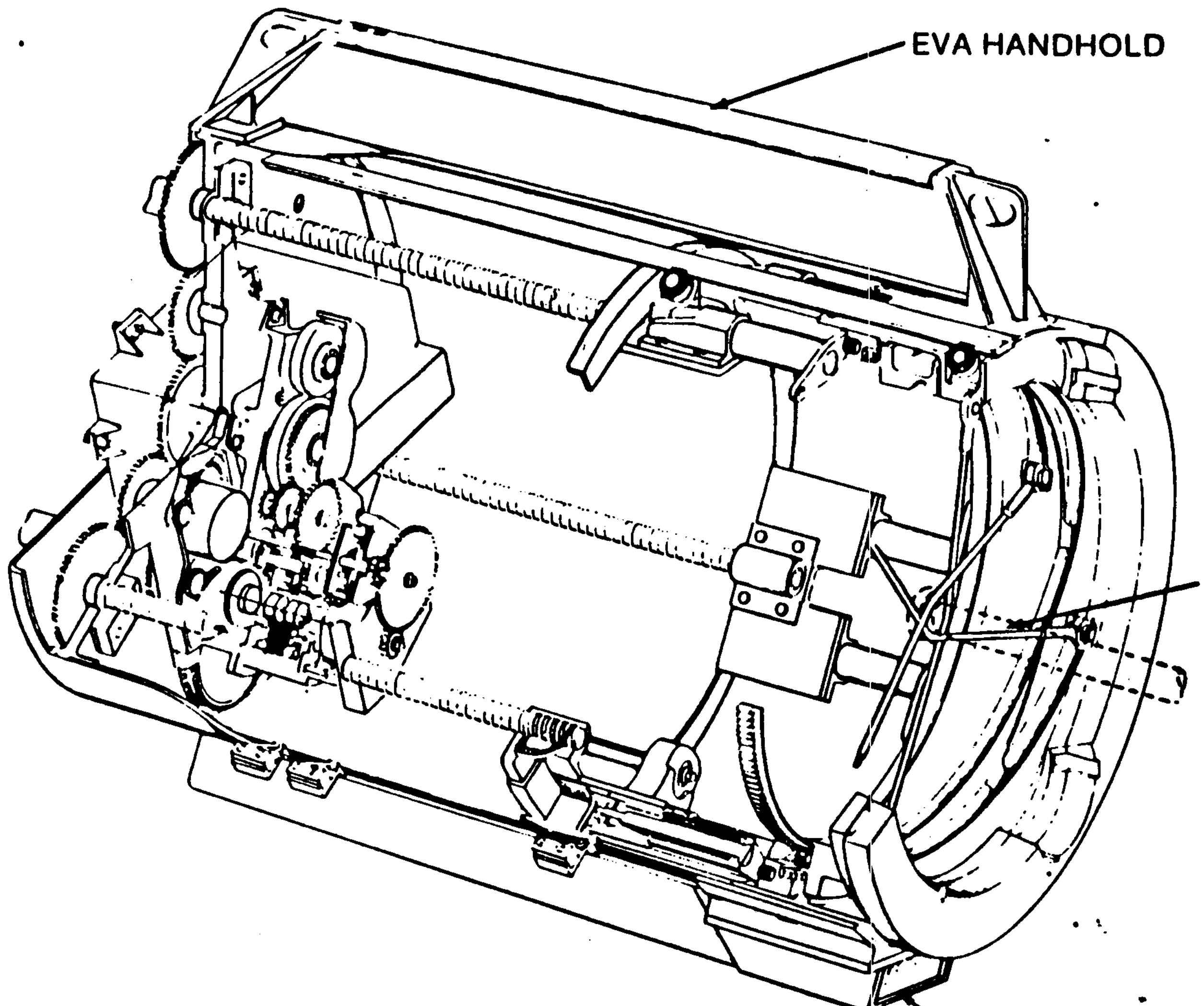


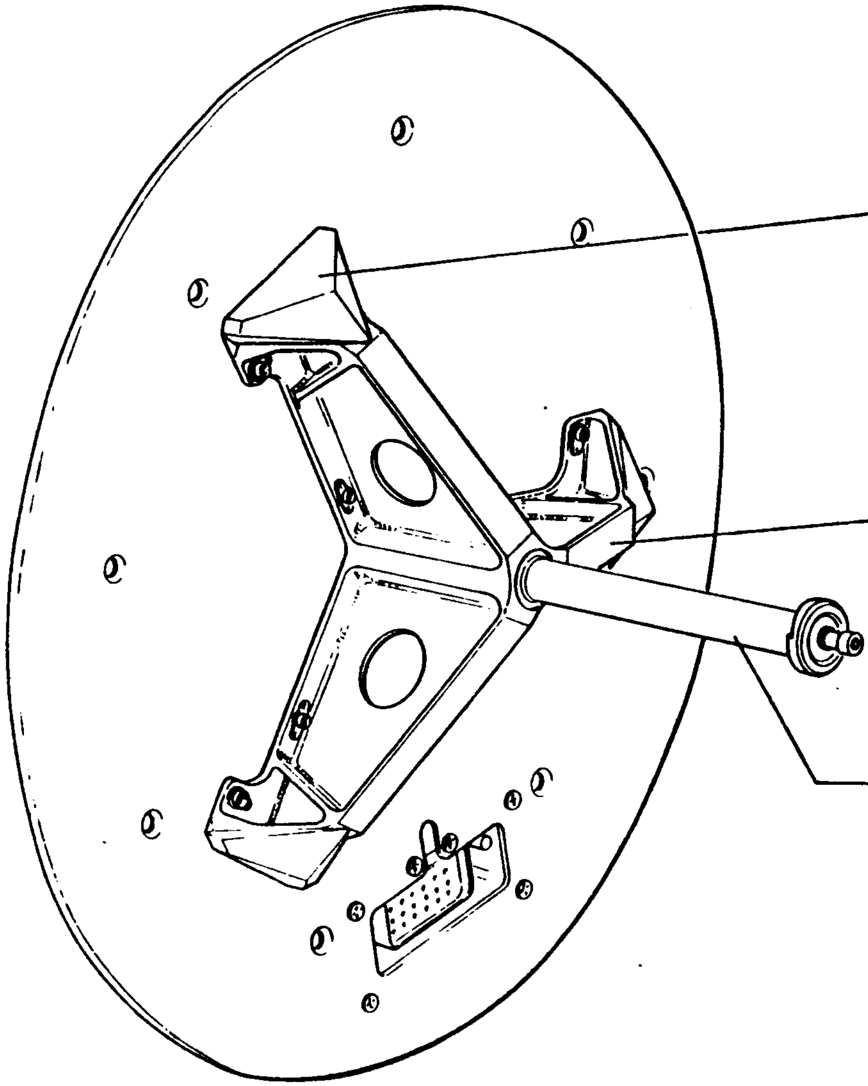

DOCKING EFFECTOR




FIRST DOCKING TOOL
(ERNO RAUMFAHRTTECHNIK GMBH)

# STANDARD SNARE TYPE END EFFECTOR






GRAPPLE FIXTURE

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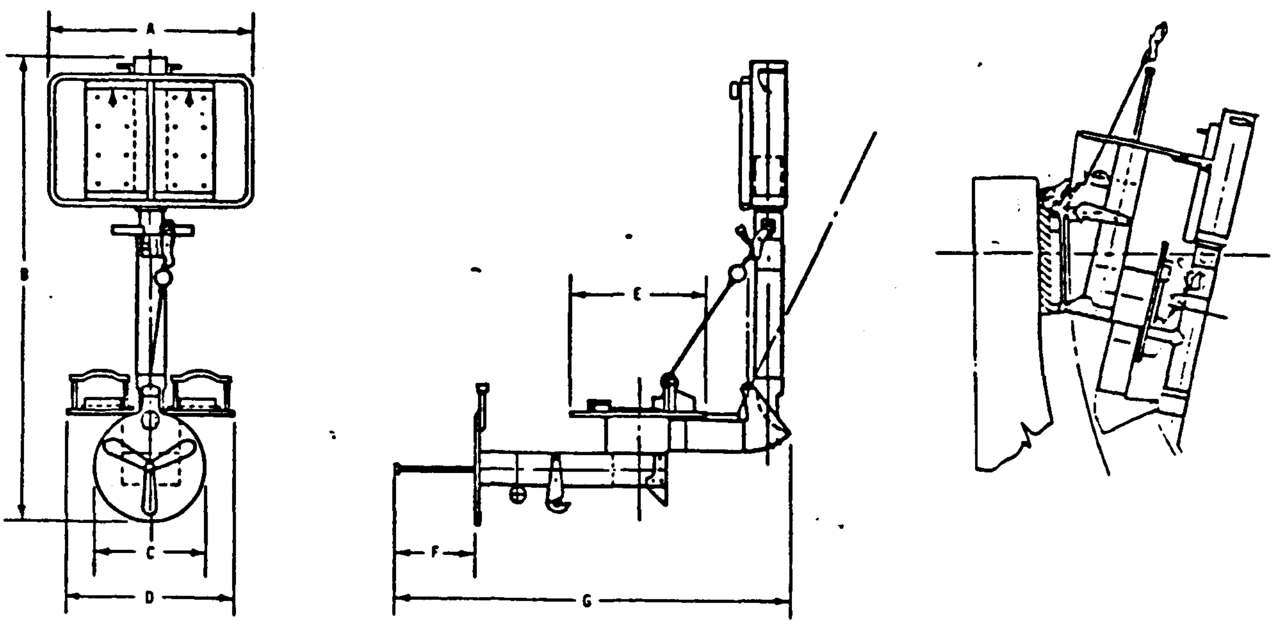
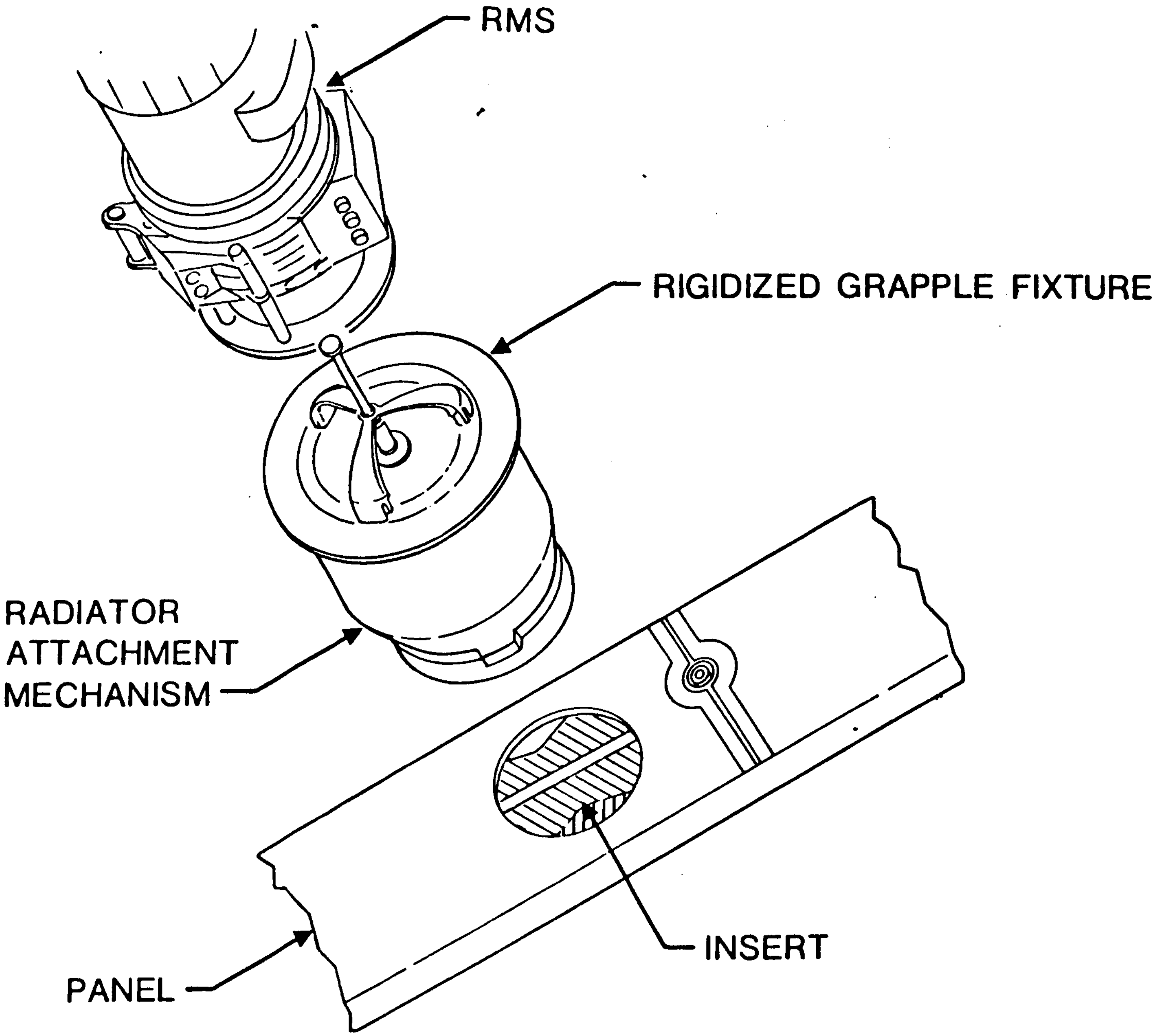
## MANIPULATOR FOOT RESTRAINT

| Technical Information | |
|---|---|
| Part number | SED33103150-305 |
| Weight | 102 lb |
| Material | Primarily aluminum |
| Rotation of MFR base including vertical stanchion | ±180° with locking in 45° increments |
| Tilt of stanchion away from crewmember | 27° forward with locking in 9° increments |
| Rotation of work station about vertical stanchion axis | ±180° with locking in 45° increments |
| Rotation of foot platform independent of base | Continuous 360° with locking in 30° increments |
| Stowage | Cargo bay, attached to APC |

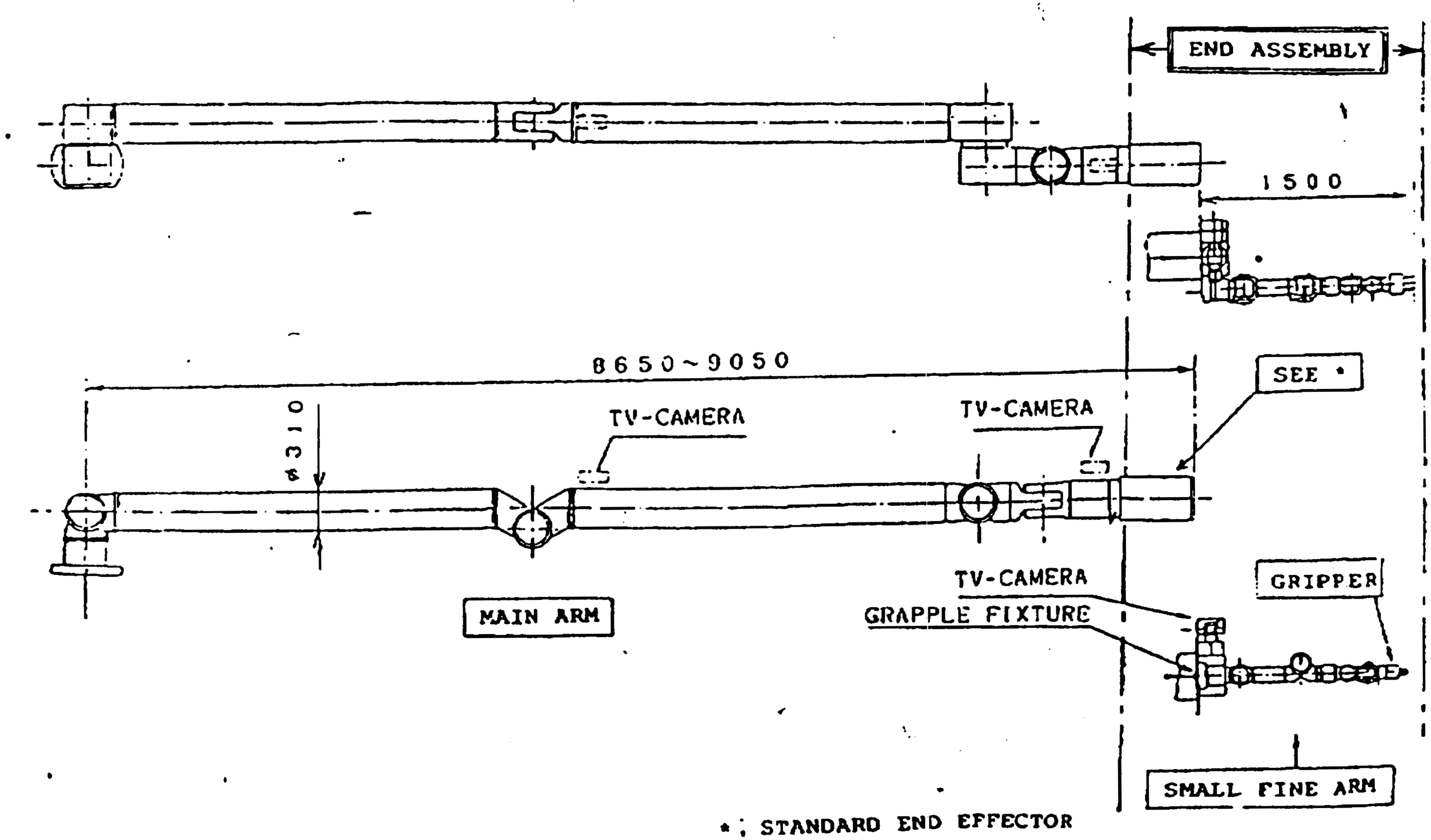
| Dimensional Data | |
|---|---|
| A | 25 in. |
| B | 61.5 in. |
| C | 14 in. |
| D | 20.5 in. |
| E | 14.5 in. |
| F | 8 in. |
| G | 52.5 in. |
| | |
| | |
| | |

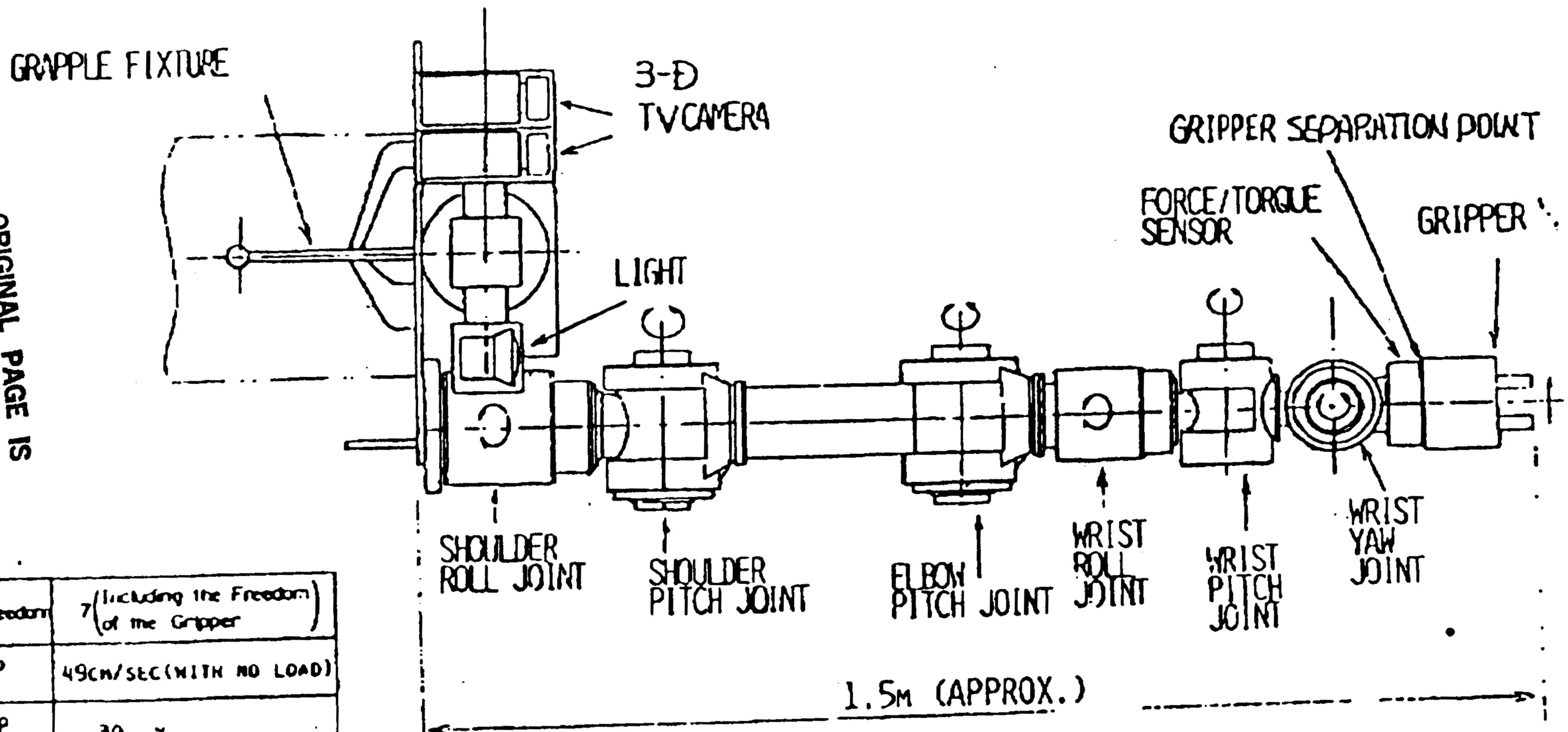


# MAGNETIC GRAPPLE CONCEPT



# JEMRMS CONFIGURATION CONCEPT

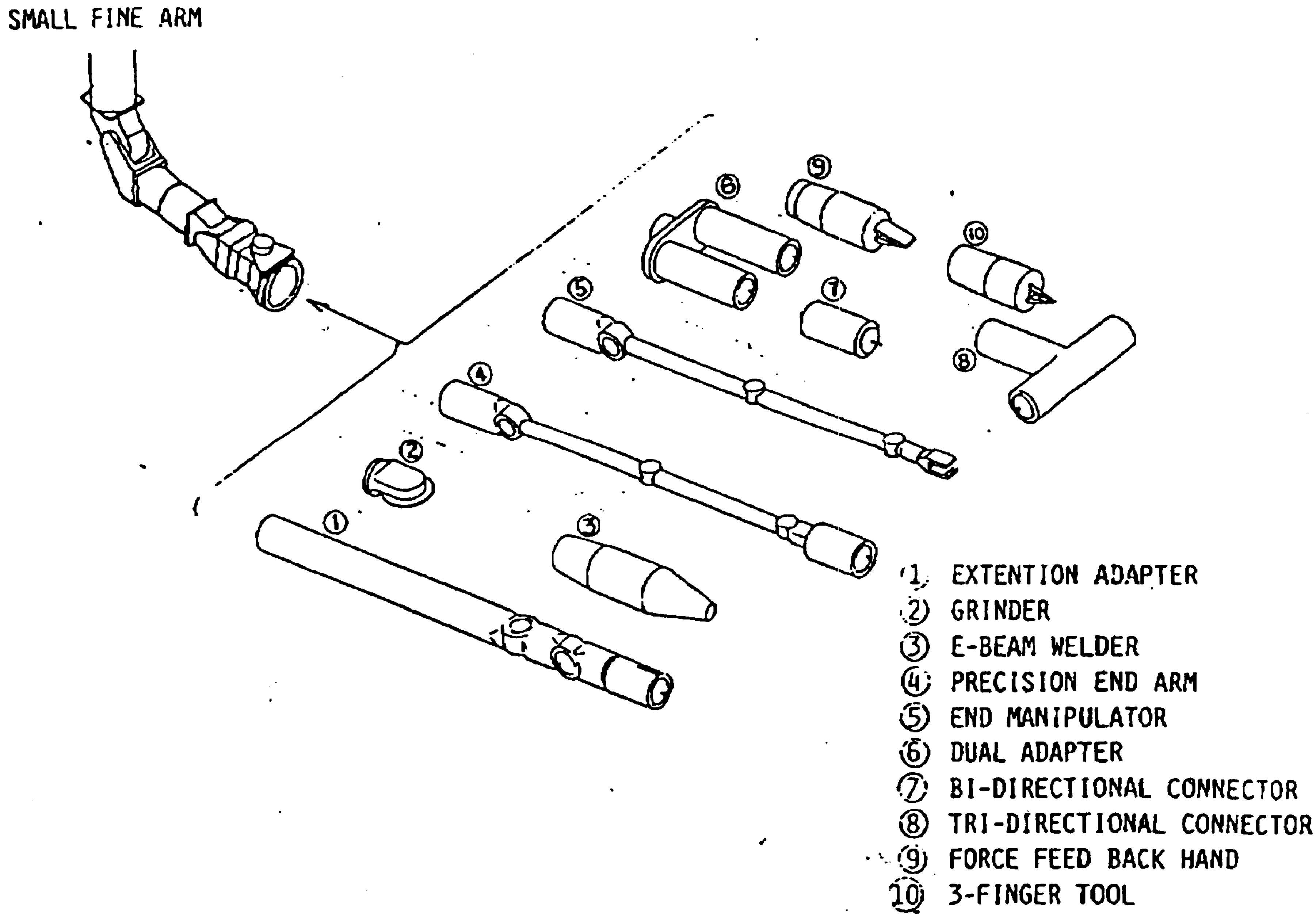




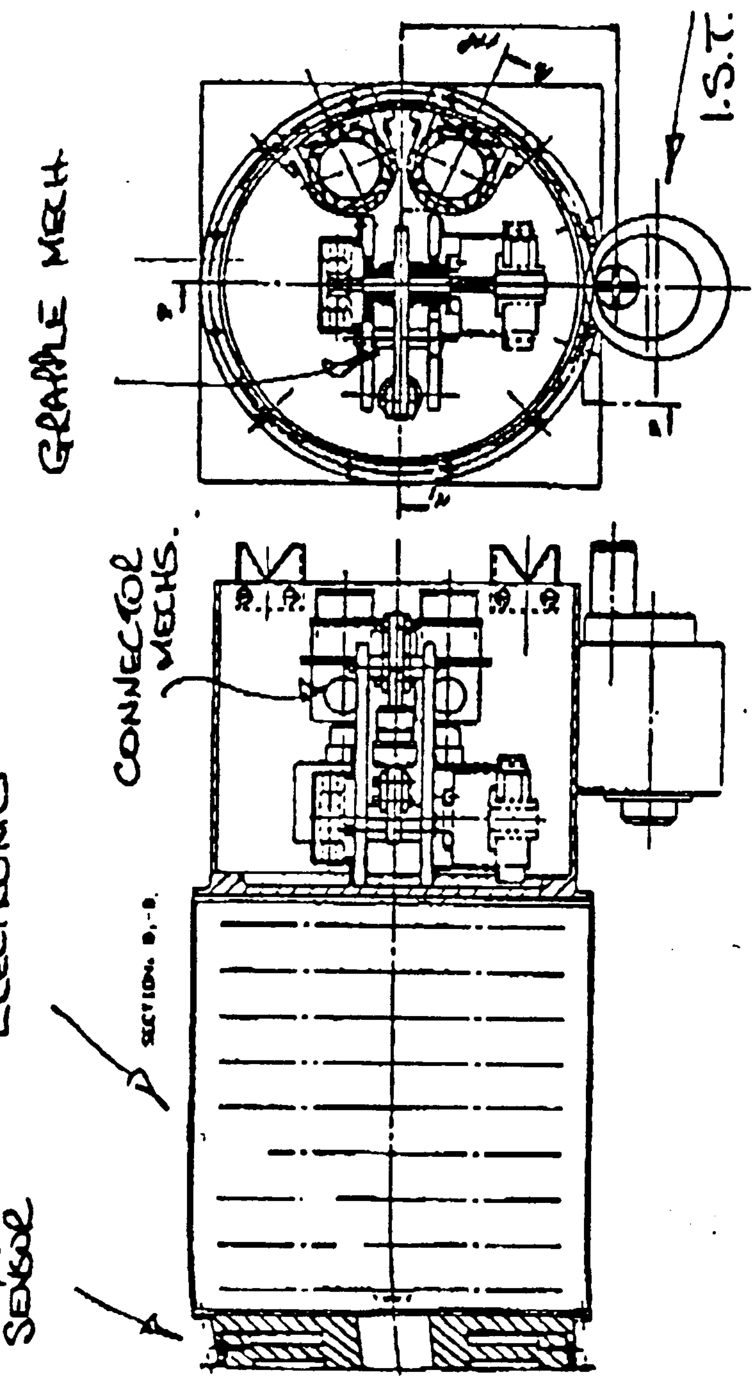



| | |
|---|---|
| Degrees of Freedom | 7 (Including the Freedom of the Gripper) |
| Maximum Tip Speed | 49CM/SEC(WITH NO LOAD) |
| Maximum Tip Force | 30 N |
| Arm Tip Accuracy | Approx ±10MM |
| Major Control Methods | Bilateral Force Reflecting (Master-Slave)<br><br>Individual Motor Control for Each Joint |

SMALL FINE ARM (LAB MODEL)




TOOLS CONCEPT




CROSS-SECTION OF BASIC E.E.

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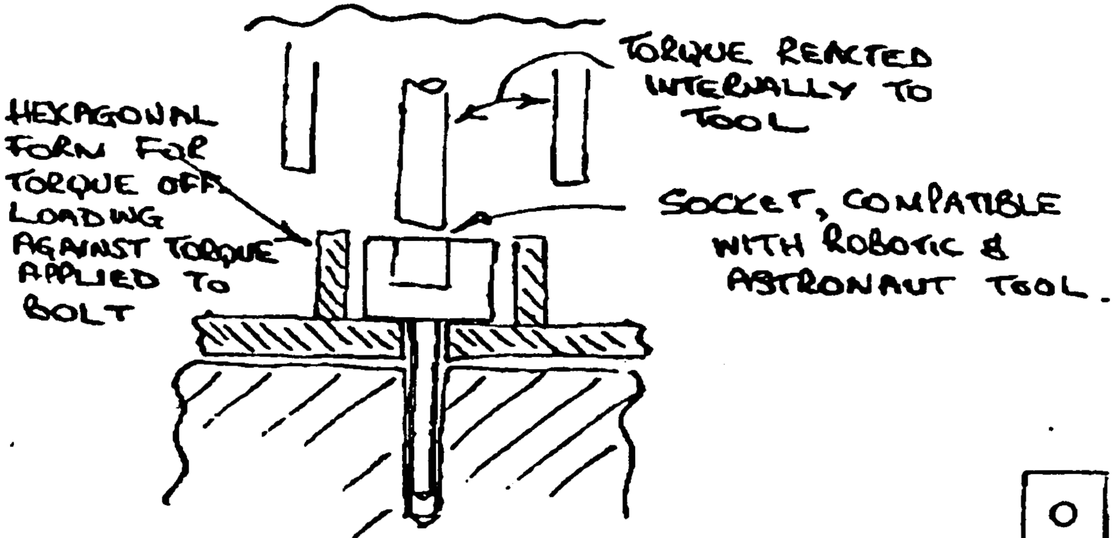
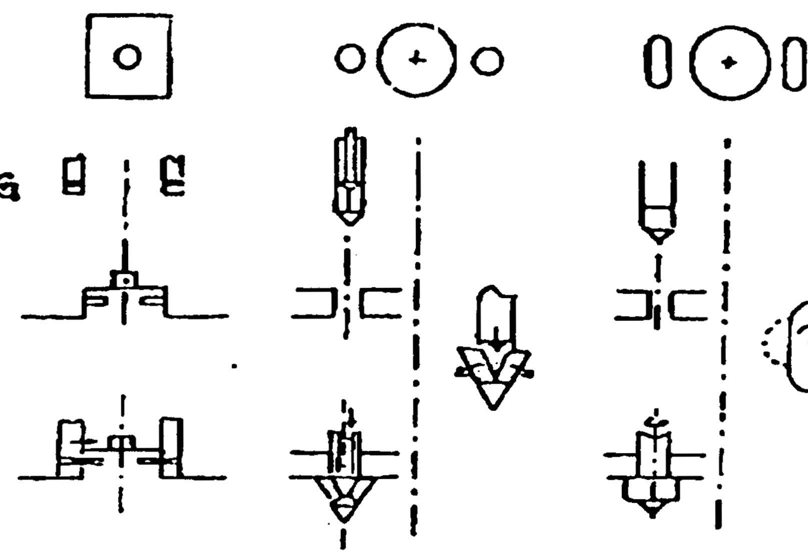
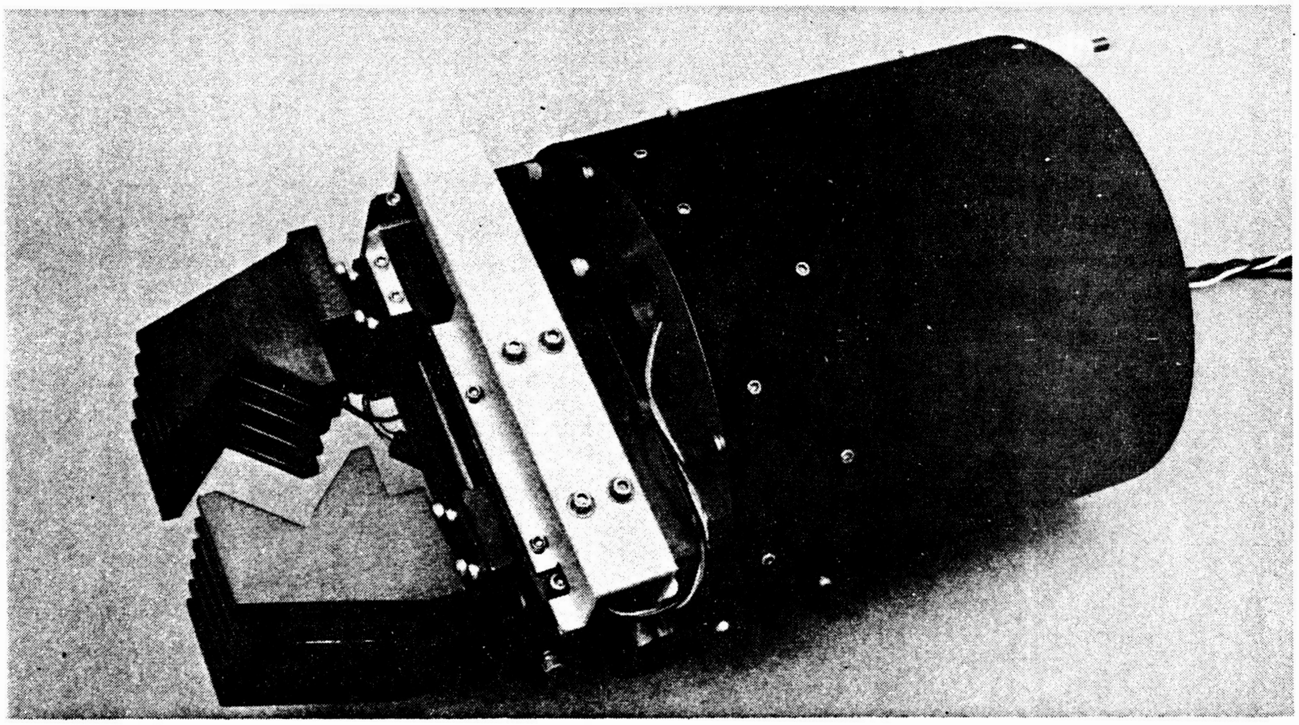


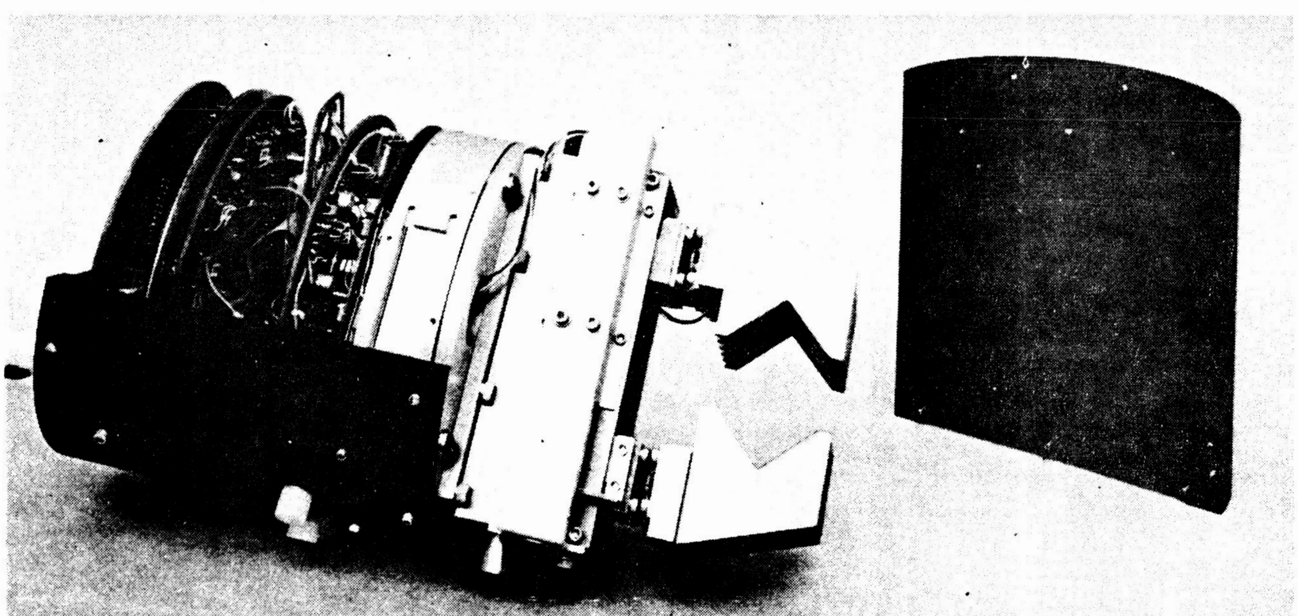

FORCE/TORQUE OFF-LOADING CONCEPT.

OTHER POSSIBLE CONCEPTS. →



JPL





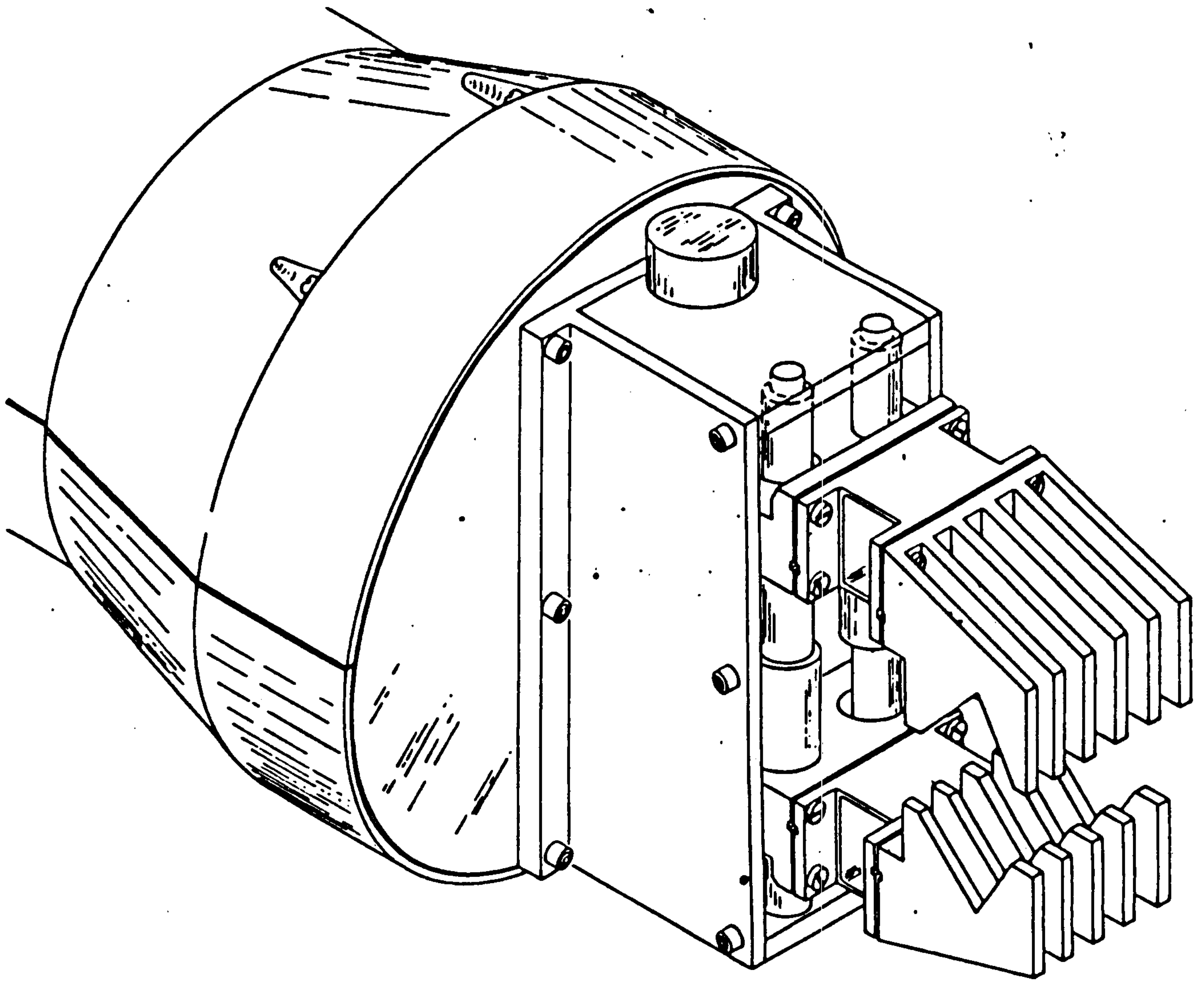
OMV Smart Hand - for PFMA

a) Upper: E/E assembly with intermeshing claws, 6 DOF Force-Moment Sensor, Grasp Force Sensors, Position Sensor, Position, Rate and Grasp Force Servo Control using Brushless DC Torque Motor, Housing of Local Electronics

b) Lower: View of Local Electronics, including three micro-computers

JPL

# OVERALL VIEW OF SERVO GRIPPER ASSEMBLY WITH WRIST FORCE AND GRASP FORCE SENSOR AND INTERMESHING CLAWS WITH TWO SUPPORT COLUMNS



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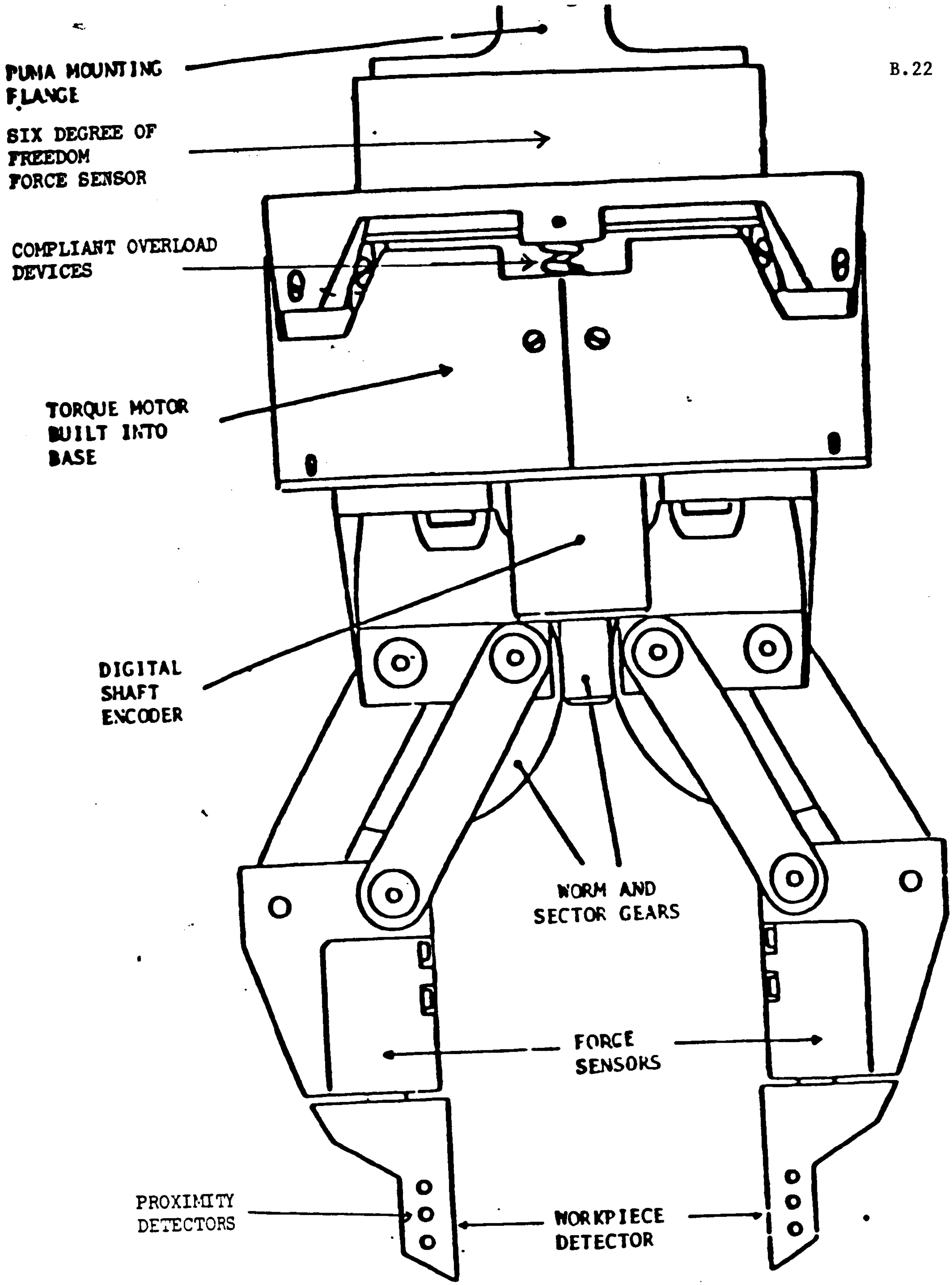
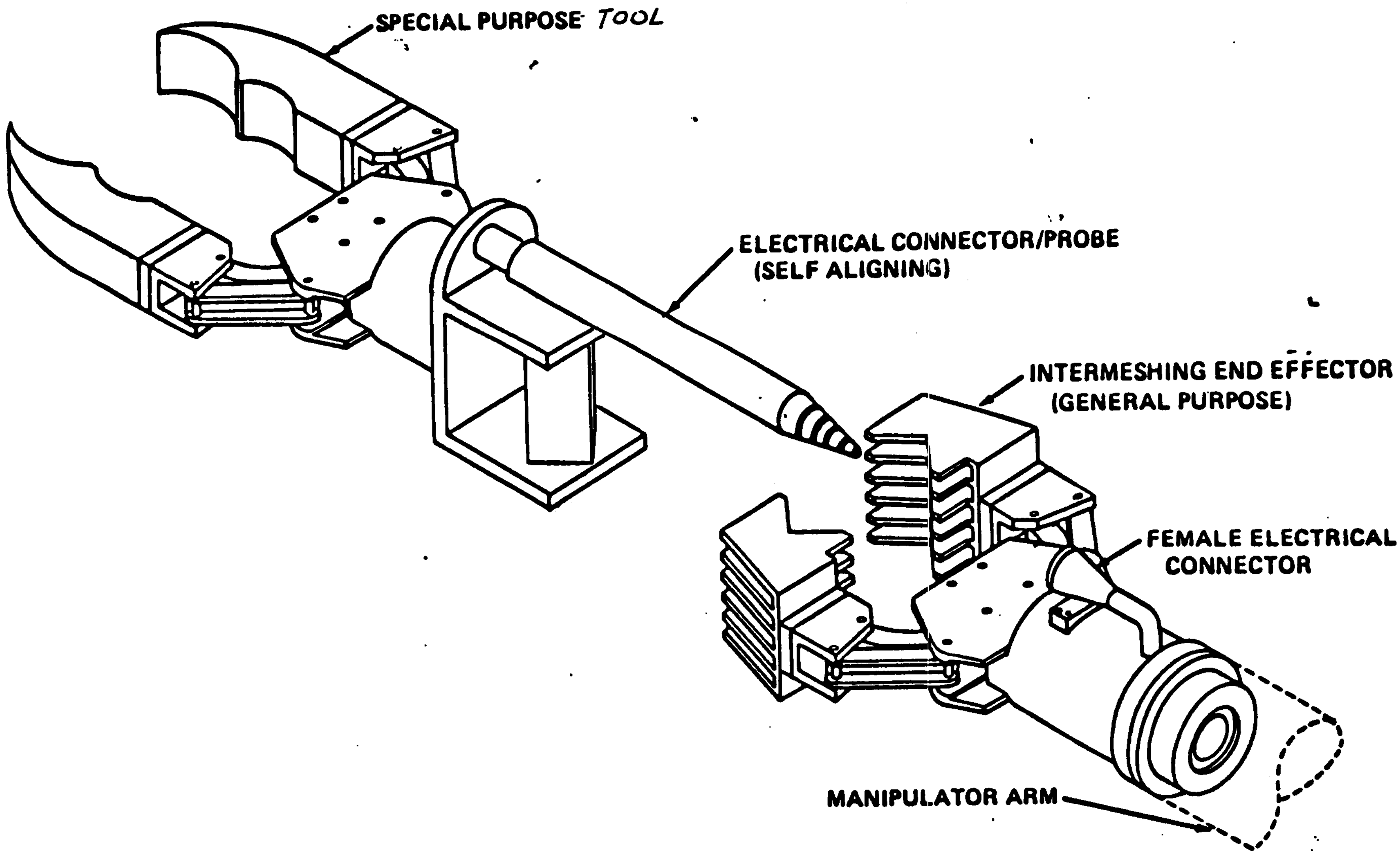
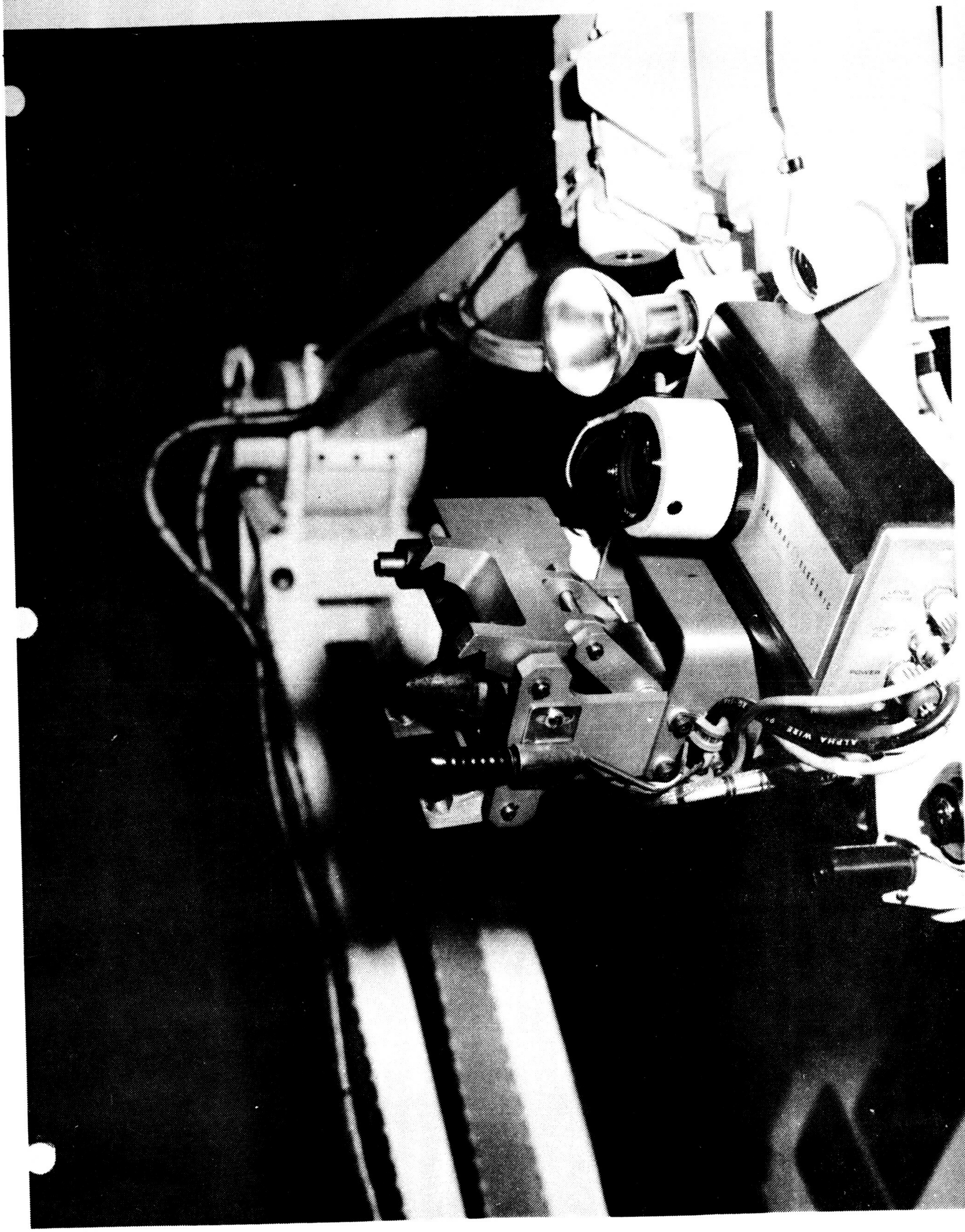

PUMA MOUNTING FLANGE
SIX DEGREE OF FREEDOM FORCE SENSOR
COMPLIANT OVERLOAD DEVICES
TORQUE MOTOR BUILT INTO BASE
DIGITAL SHAFT ENCODER
WORM AND SECTOR GEARS
FORCE SENSORS
PROXIMITY DETECTORS
WORKPIECE DETECTOR

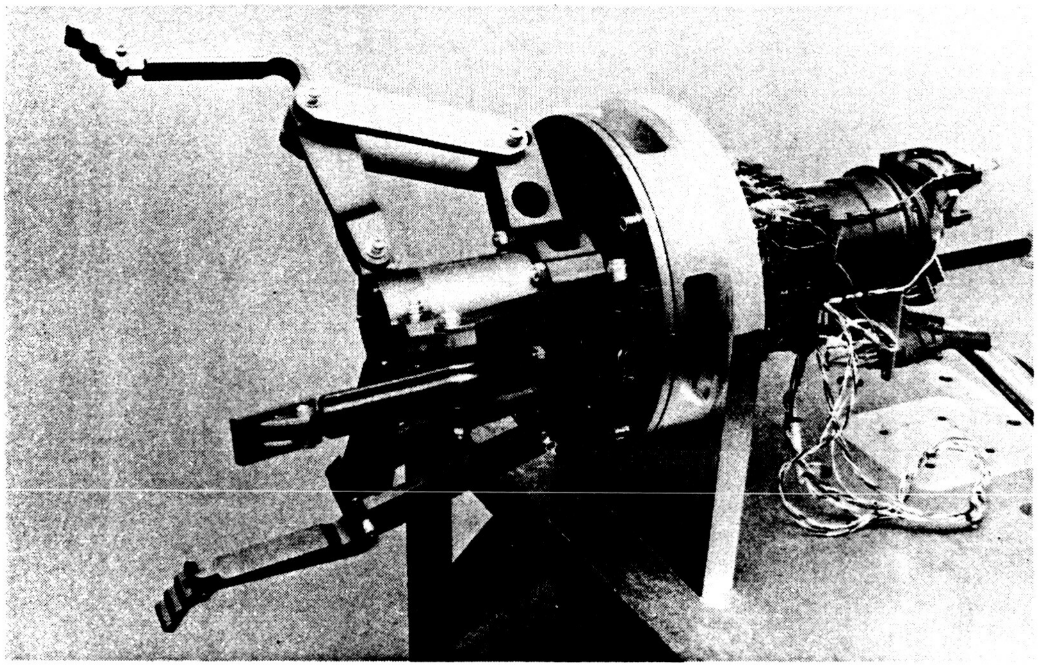


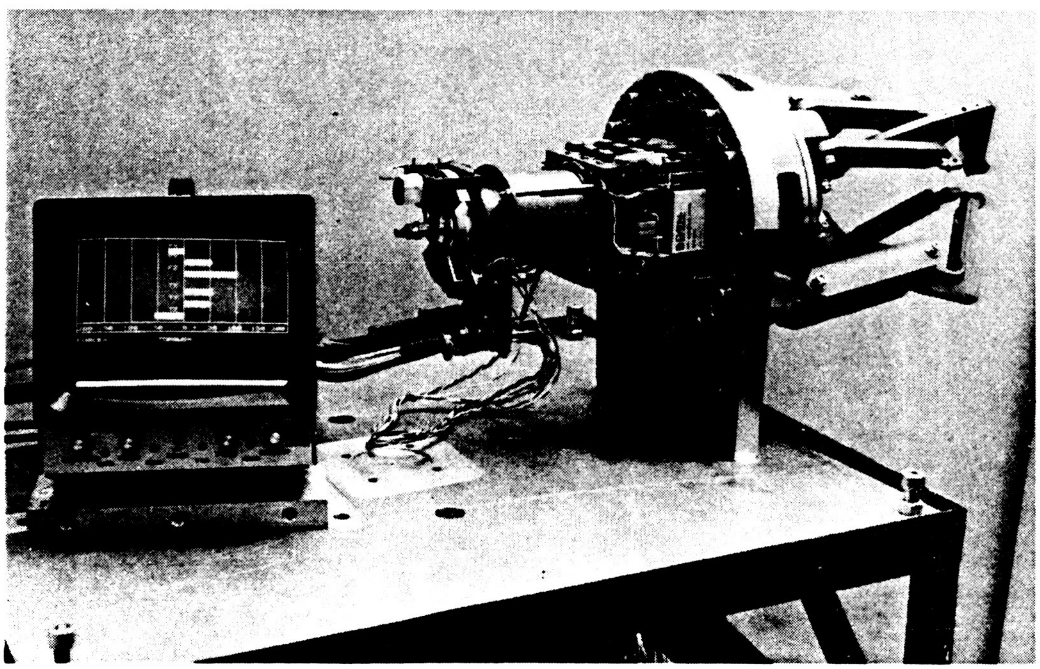

END EFFECTOR TOOL INTERFACE

IOSS MODULE END EFFECTOR - MSFC



JPL



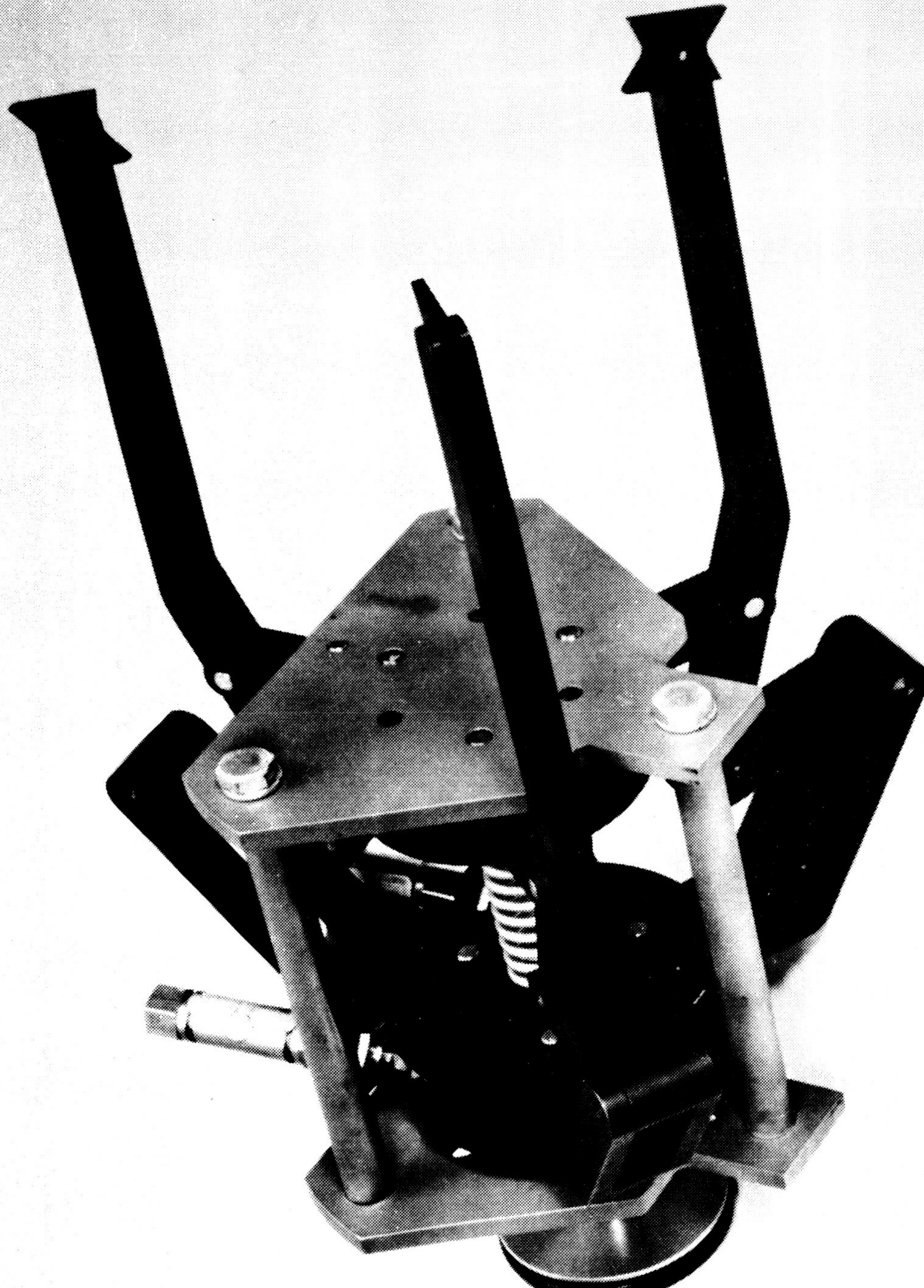


RMS Claw End Effector with 6 DOF Force-Moment Sensor and Brushless DC Motor Drive for Position and Rate Servo

a) Upper: Three-Claw Assembly with Hinged Claw Tips

b) Lower: Four-Claw Assembly and Graphics Display

# THE VERSAGRIP III



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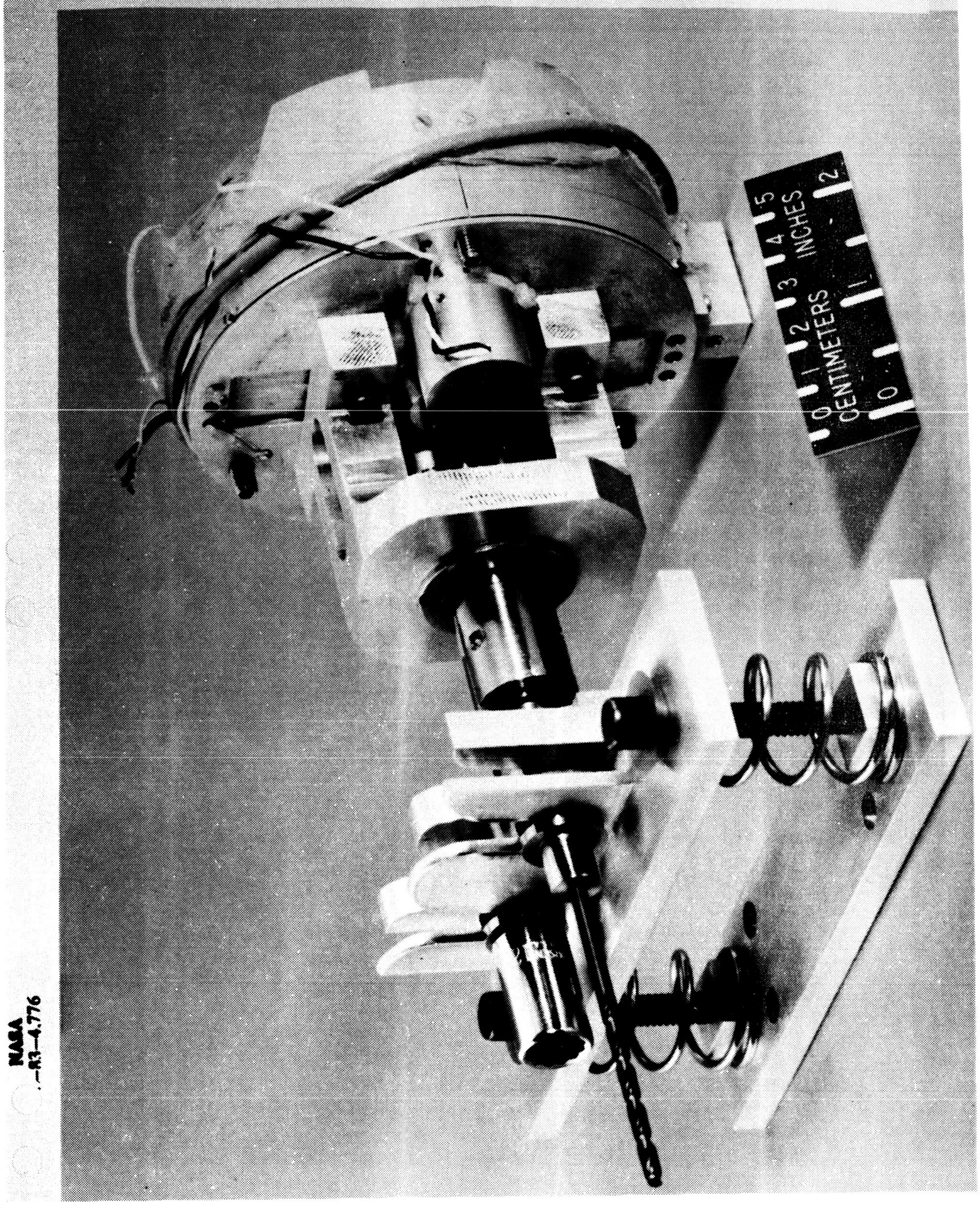
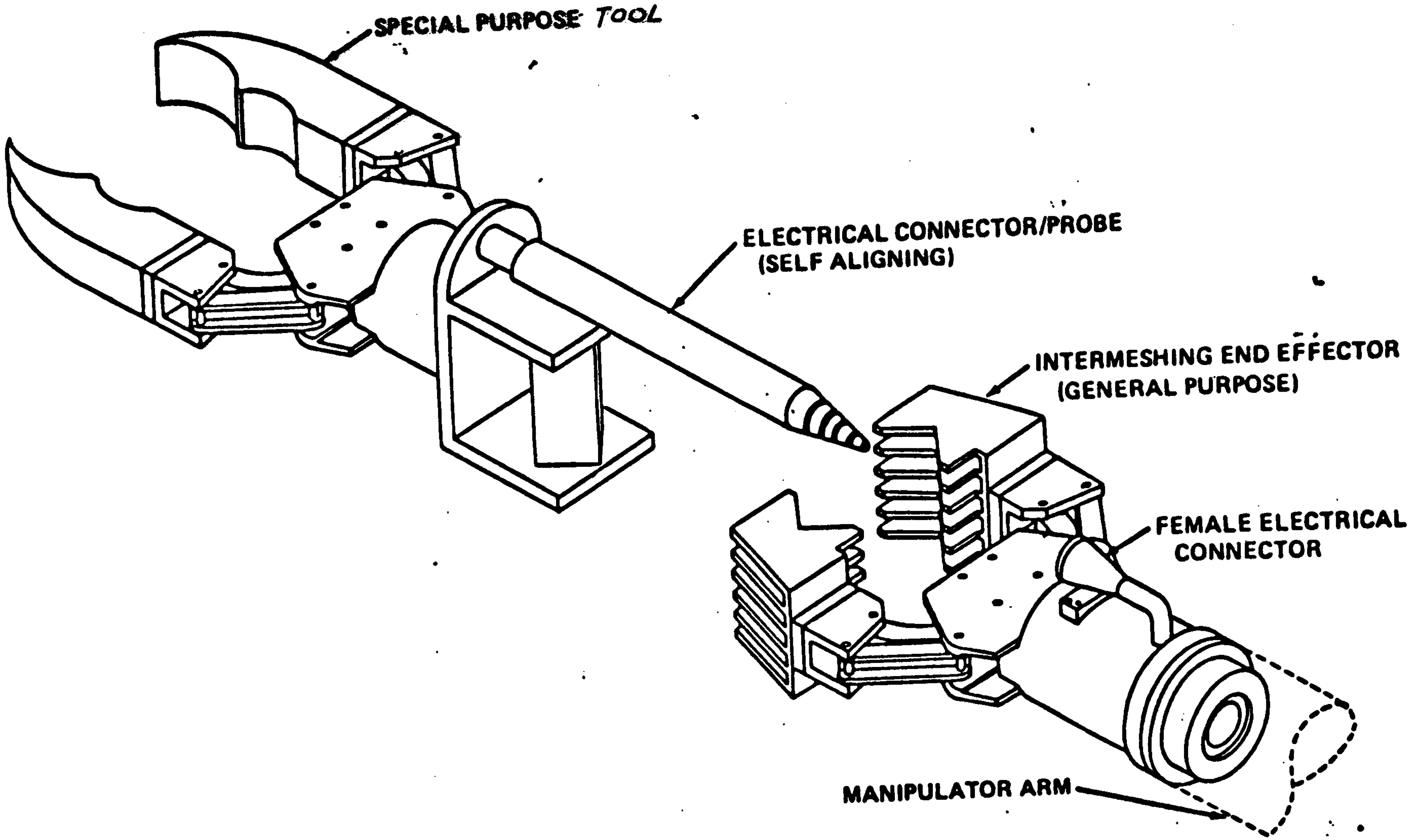
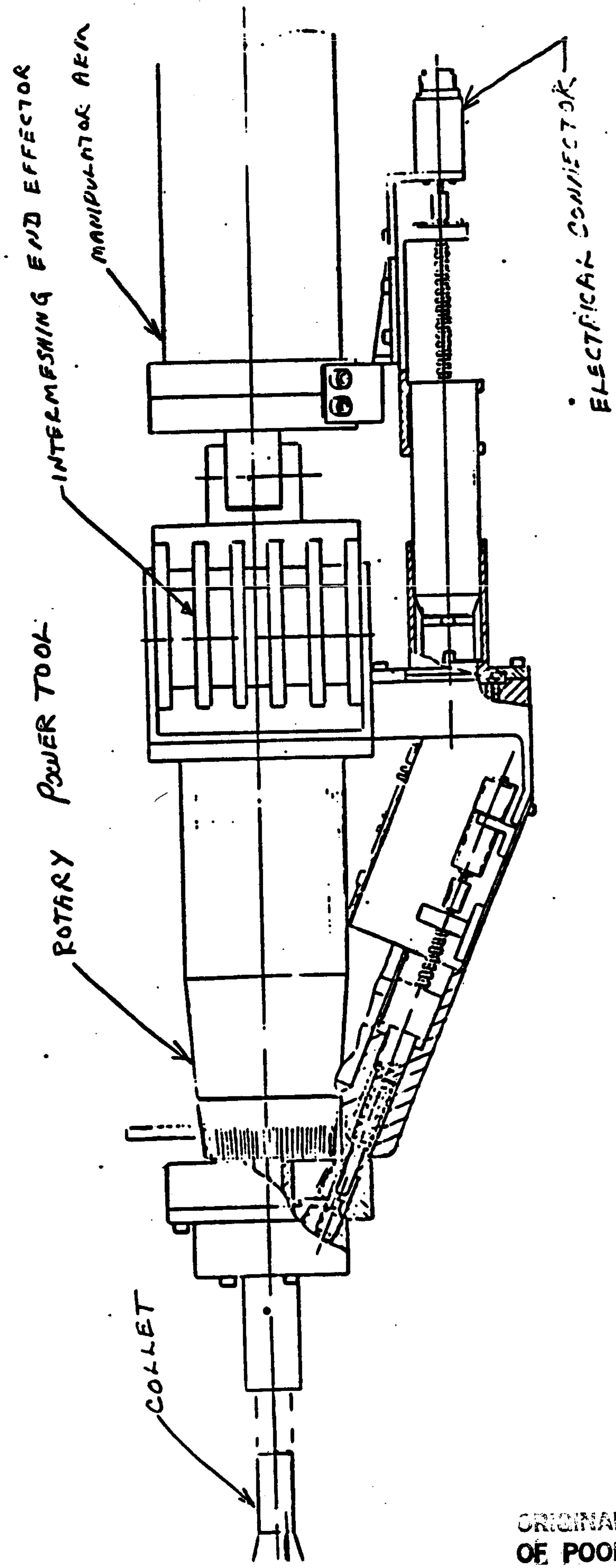
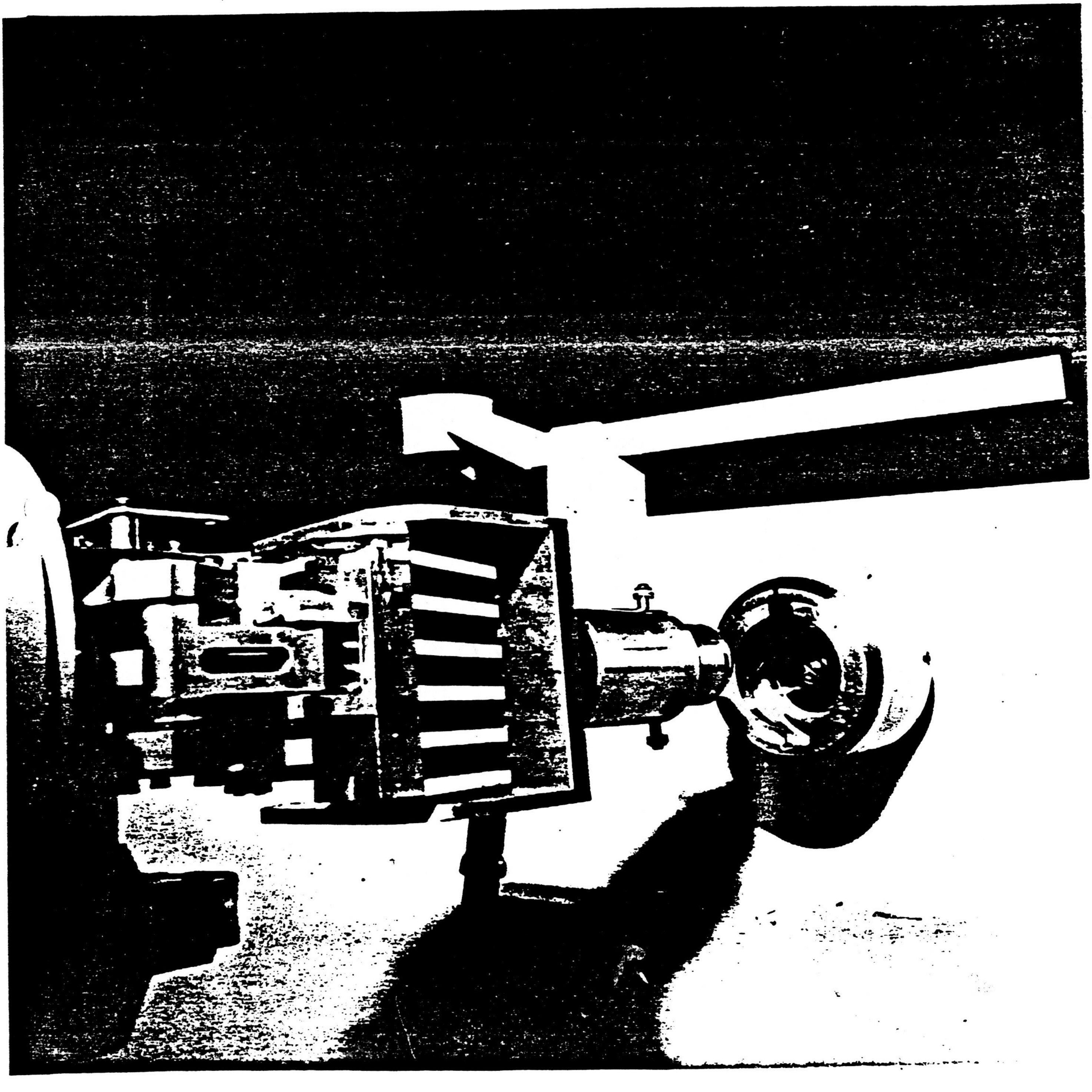
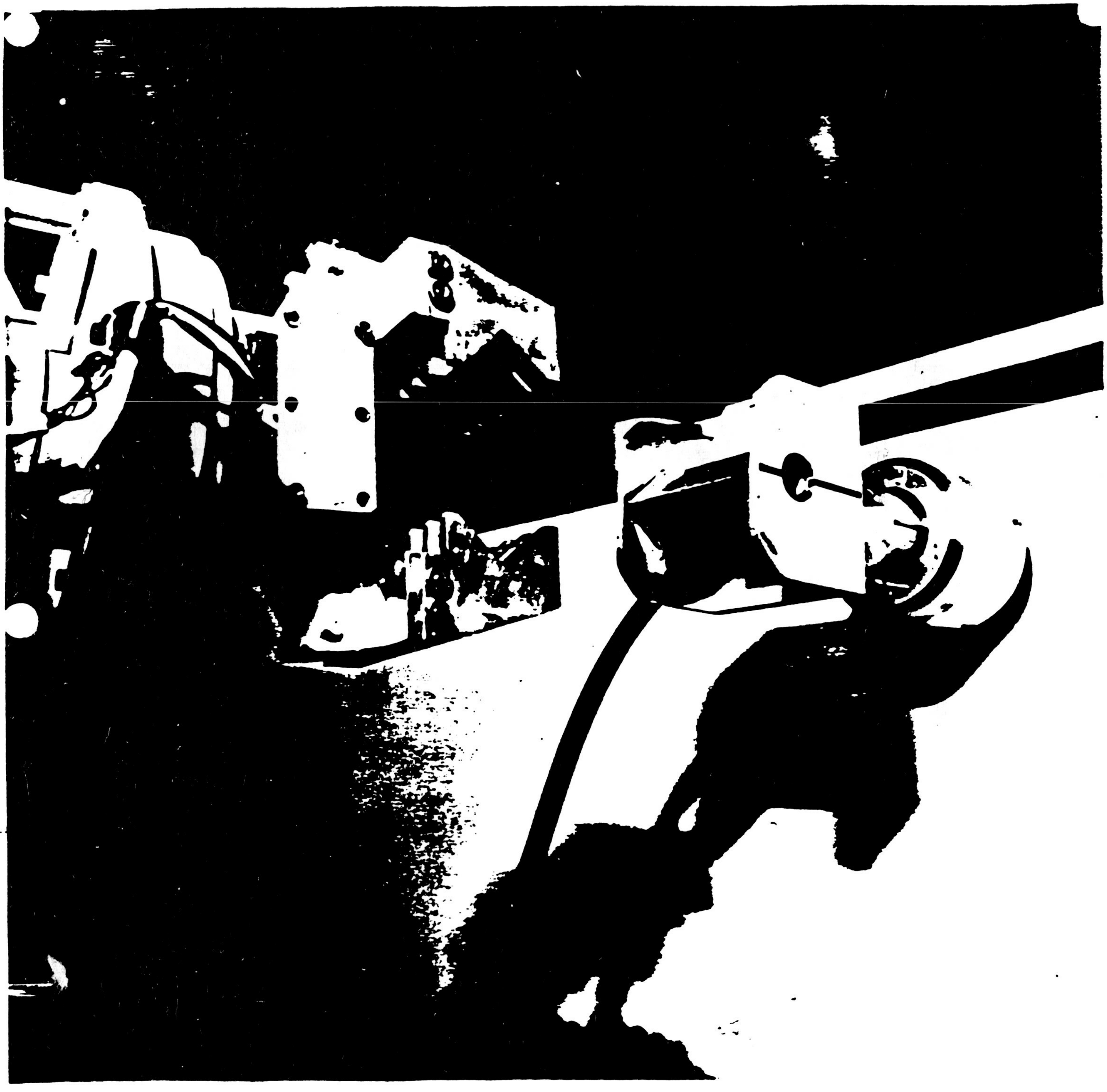





END EFFECTOR TOOL INTERFACE


MANIPULATOR ARM
INTERMESHING END EFFECTOR
ELECTRICAL CONNECTOR
ROTARY POWER TOOL
COLLET

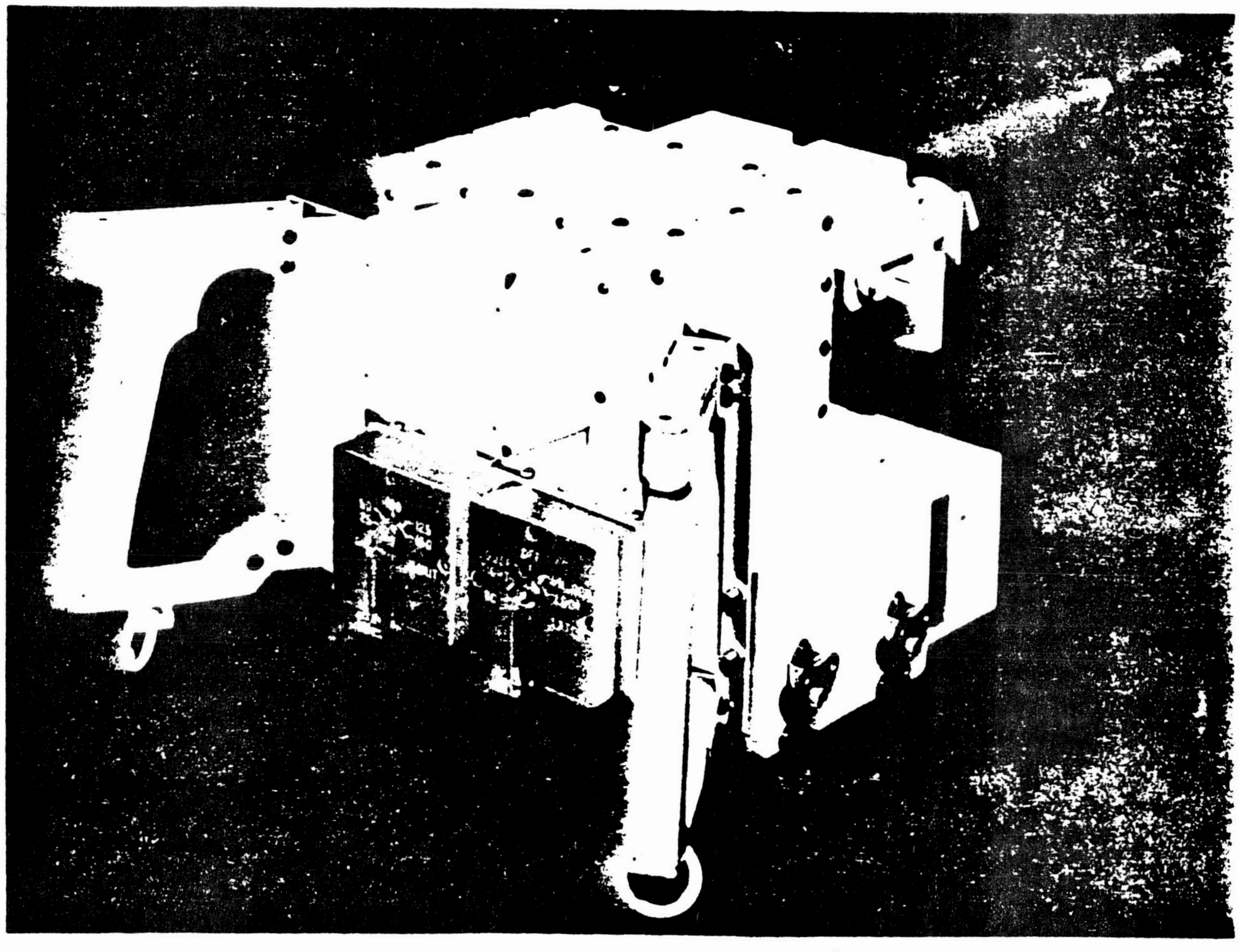




# MODULE SERVICE TOOL

## Overview

The Module Service Tool (MST) is a self-contained hand tool for use in installing and removing standard Multimission Modular Spacecraft (MMS) subsystem modules to simplify on-orbit maintenance and repair operations and to reduce the time required for the performance of extravehicular activities (EVA's).



## Performance Description

The MST is a battery-powered EVA hand tool which is designed to loosen and tighten the MMS module retention hardware to predetermined torques of up to 160 ft-lb. It provides a means for locking onto the modules in a manner which prevents reaction rotational torques on the crew member. Power is supplied by an Extravehicular Mobility Unit battery housed in the tool assembly.

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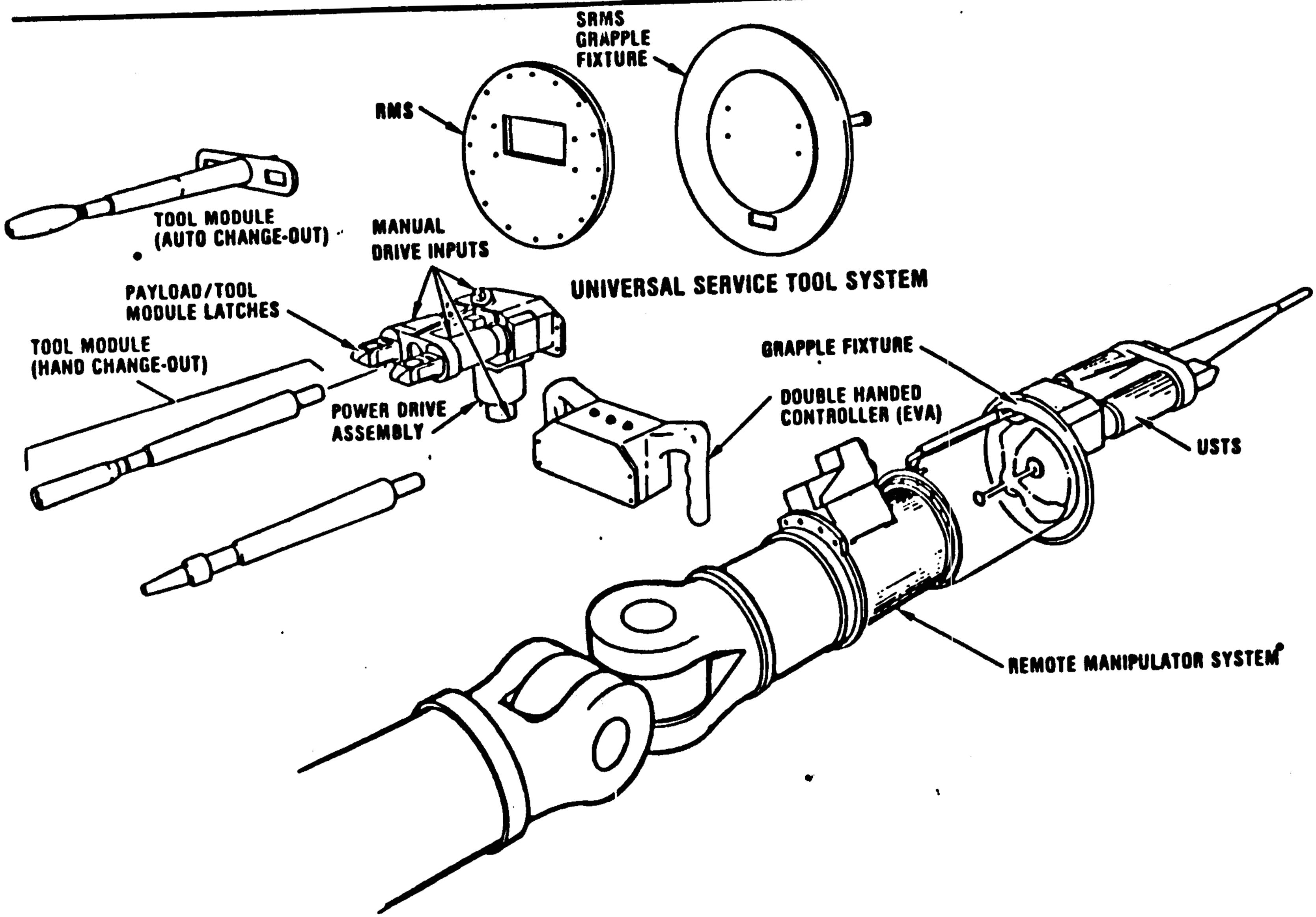
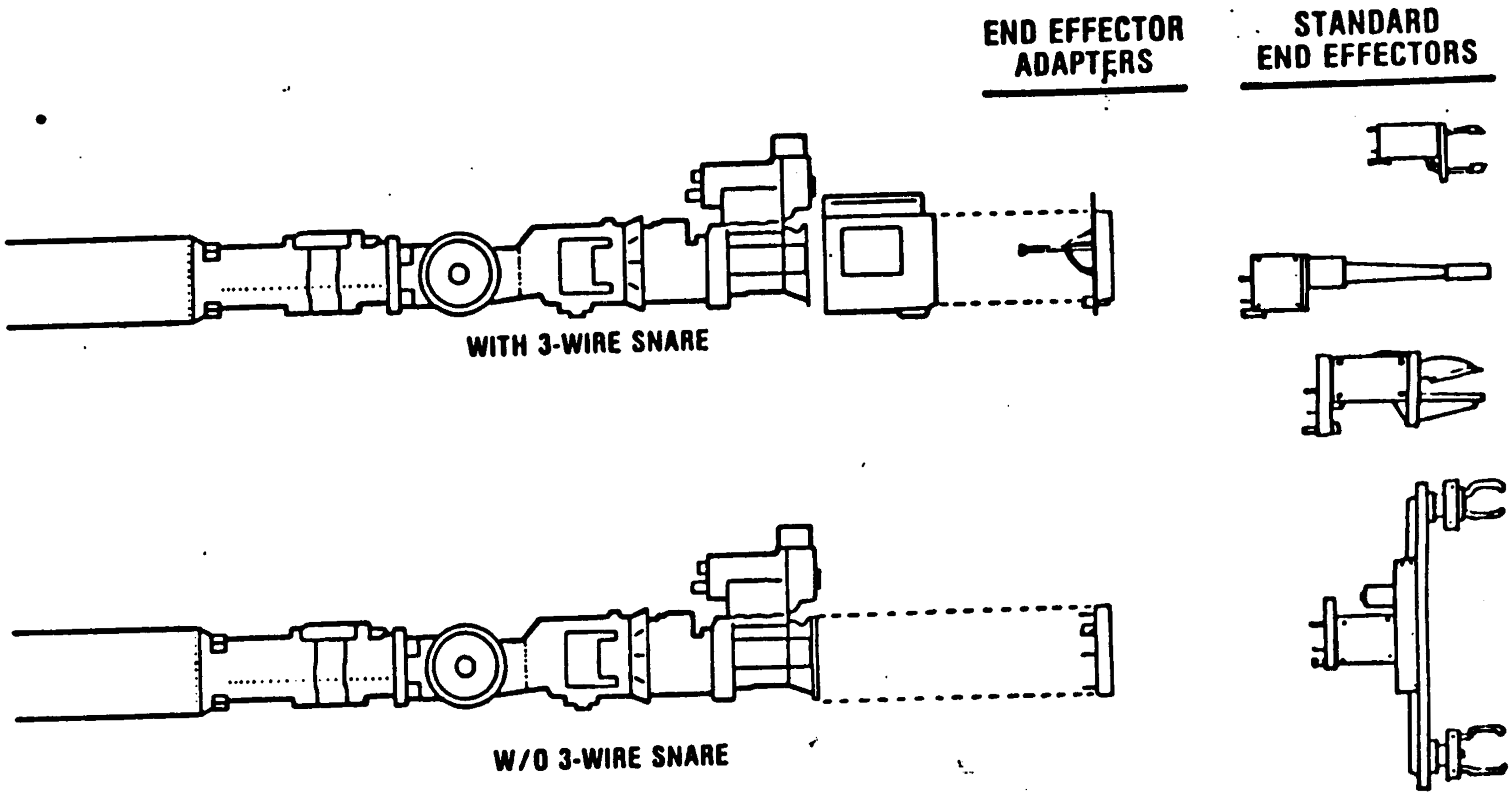
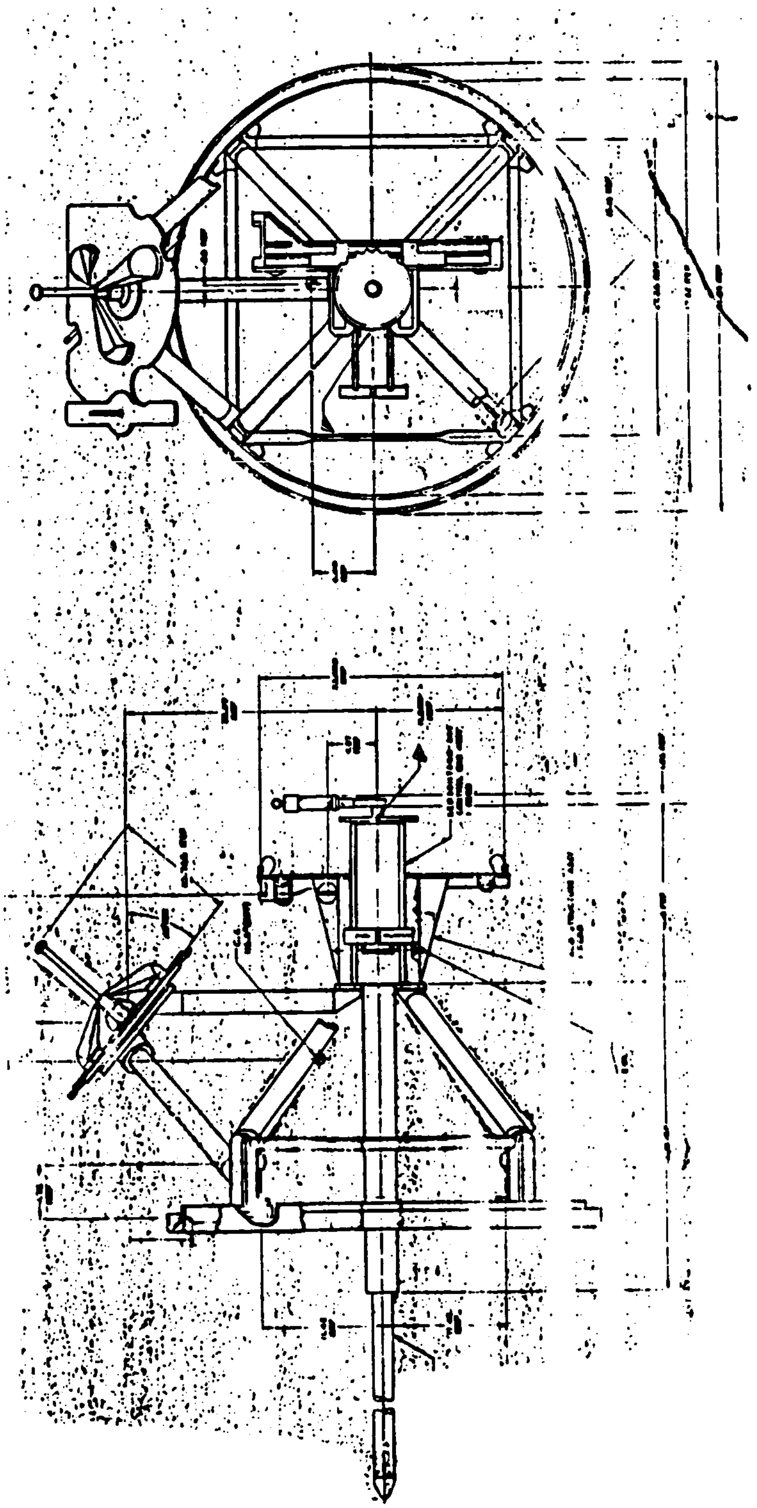
# Universal Service Tool System Used on MRMS



# MRMS Has End Effector Interchangeability



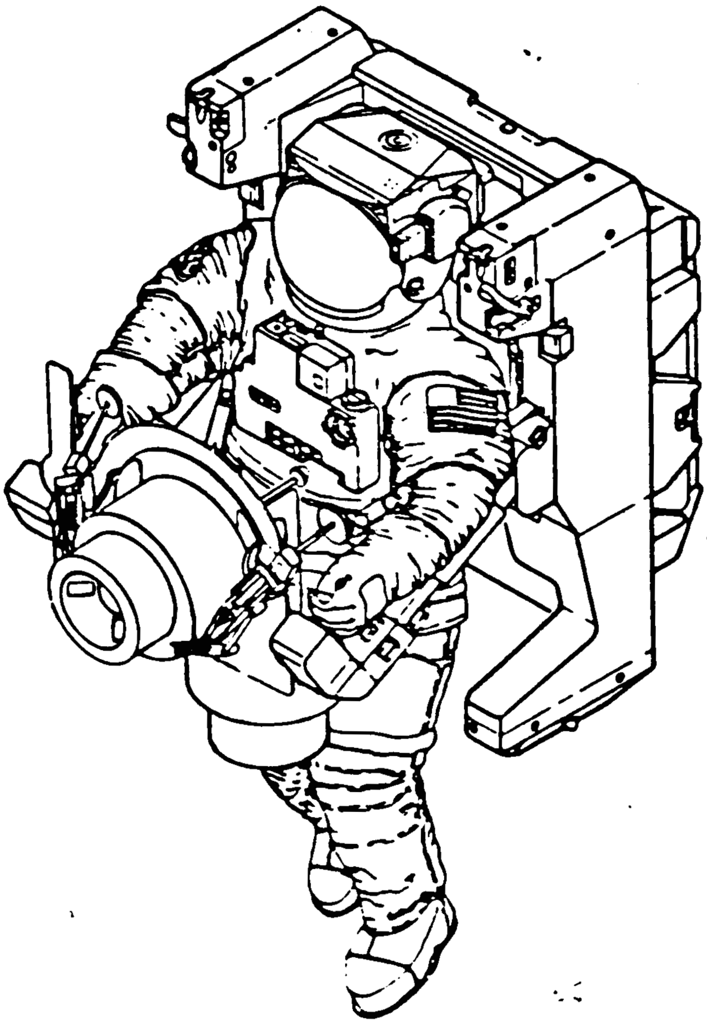


AKM CAPTURE DEVICE (ACD)

# TRUNNION PIN ATTACHMENT DEVICE

## Overview

The Trunnion Pin Attachment Device (TPAD), which is mounted on the Manned Maneuvering Unit (MMU), provides the extravehicular crew member a means of attaching a grapple fixture to a satellite trunnion pin, thus allowing control of the satellite.



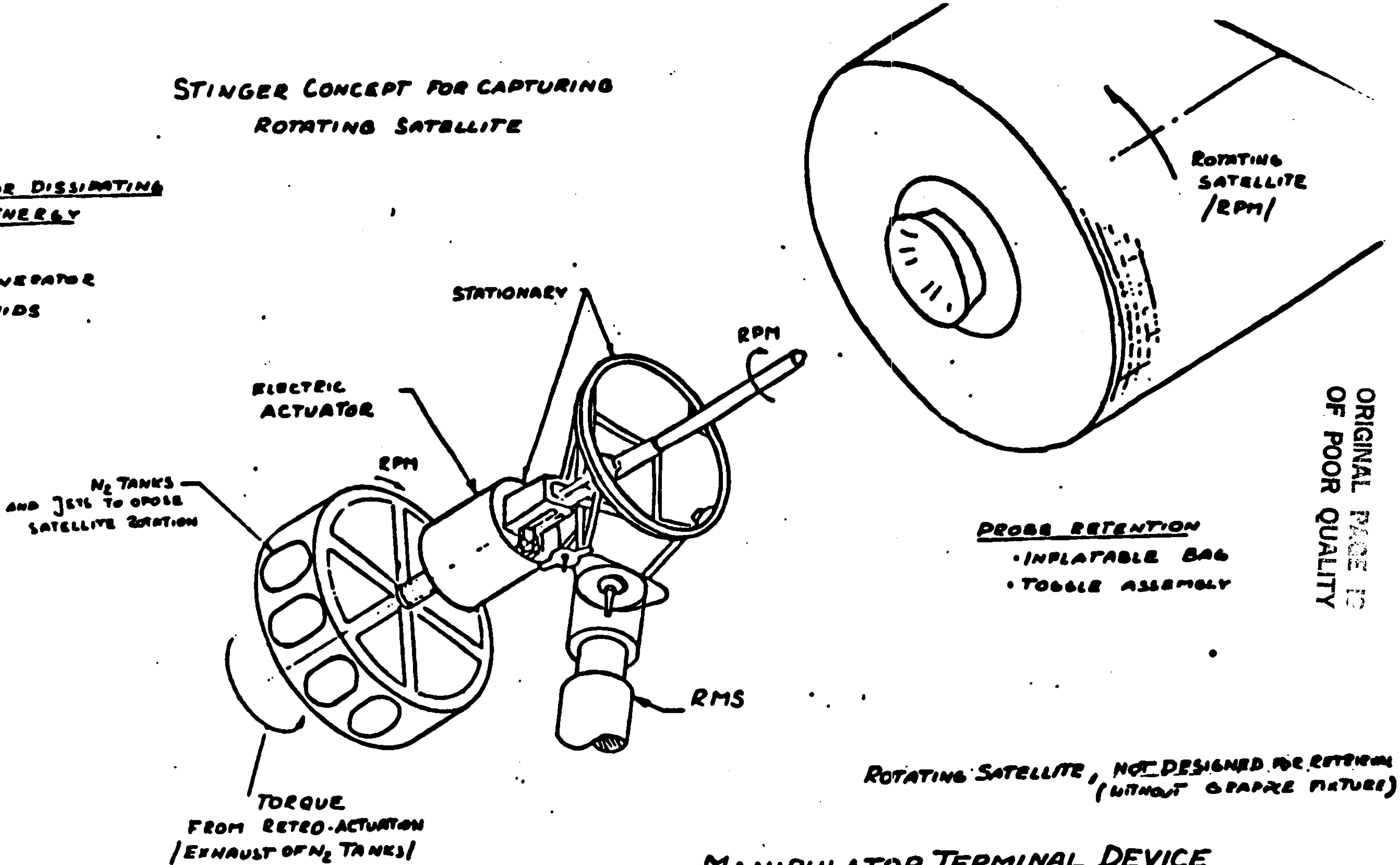
## Performance Description

The basic TPAD structure consists of two assemblies - the TPAD control assembly and the secondary TPAD assembly - both of which are attached to the MMU by two mounting brackets. The control assembly provides the crew member with TPAD jaw action and locking control and contains provisions for disconnecting the TPAD jaw assembly from the control assembly. The secondary TPAD attaches the crew member to the satellite in

STINGER CONCEPT FOR CAPTURING
ROTATING SATELLITE

ALTERNATES FOR DISSIPATING ENERGY

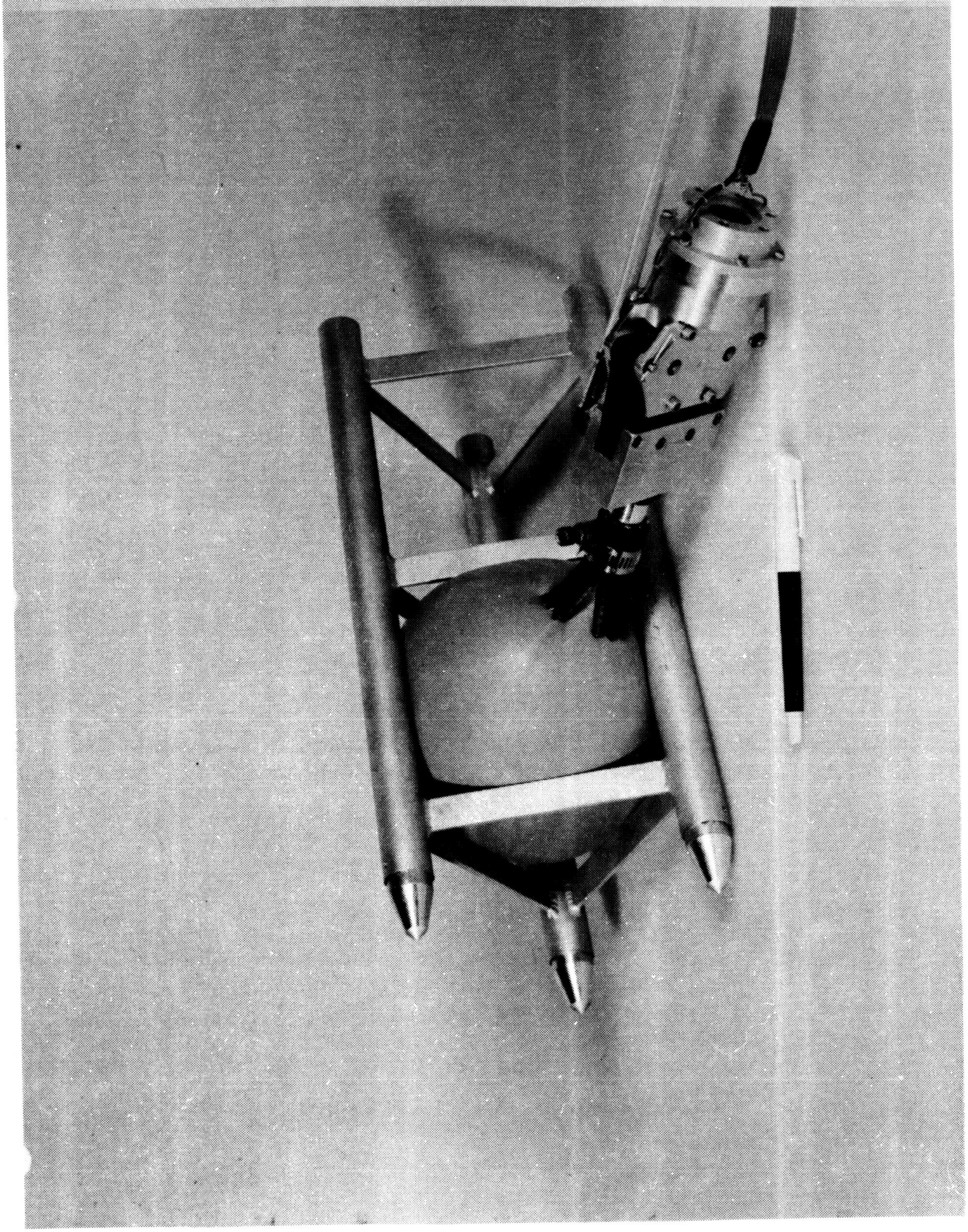
- BRAKES
- ELECTRIC GENERATOR
- VISCOUS FLUIDS



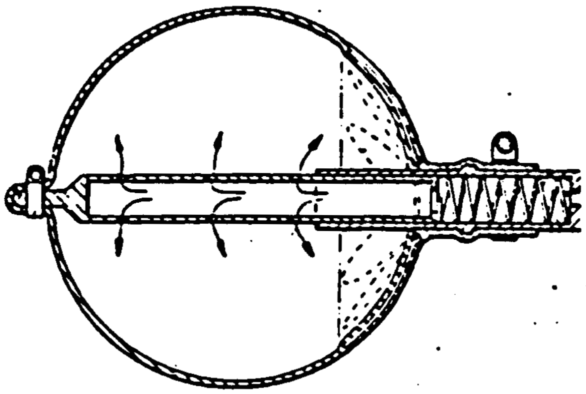



MANIPULATOR TERMINAL DEVICE
CAPTURE OF SATELLITE -CONCEPT-
AKM + $N_2$ WHEEL + ELECTRIC ACTUATOR

EE CONCEPT



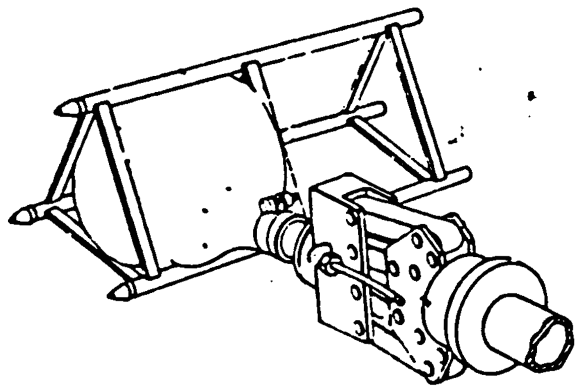
INTERNAL GRASP VARIABLE GEOMETRY



REF. U.S. PATENT #4,273,505 - Clark, et al

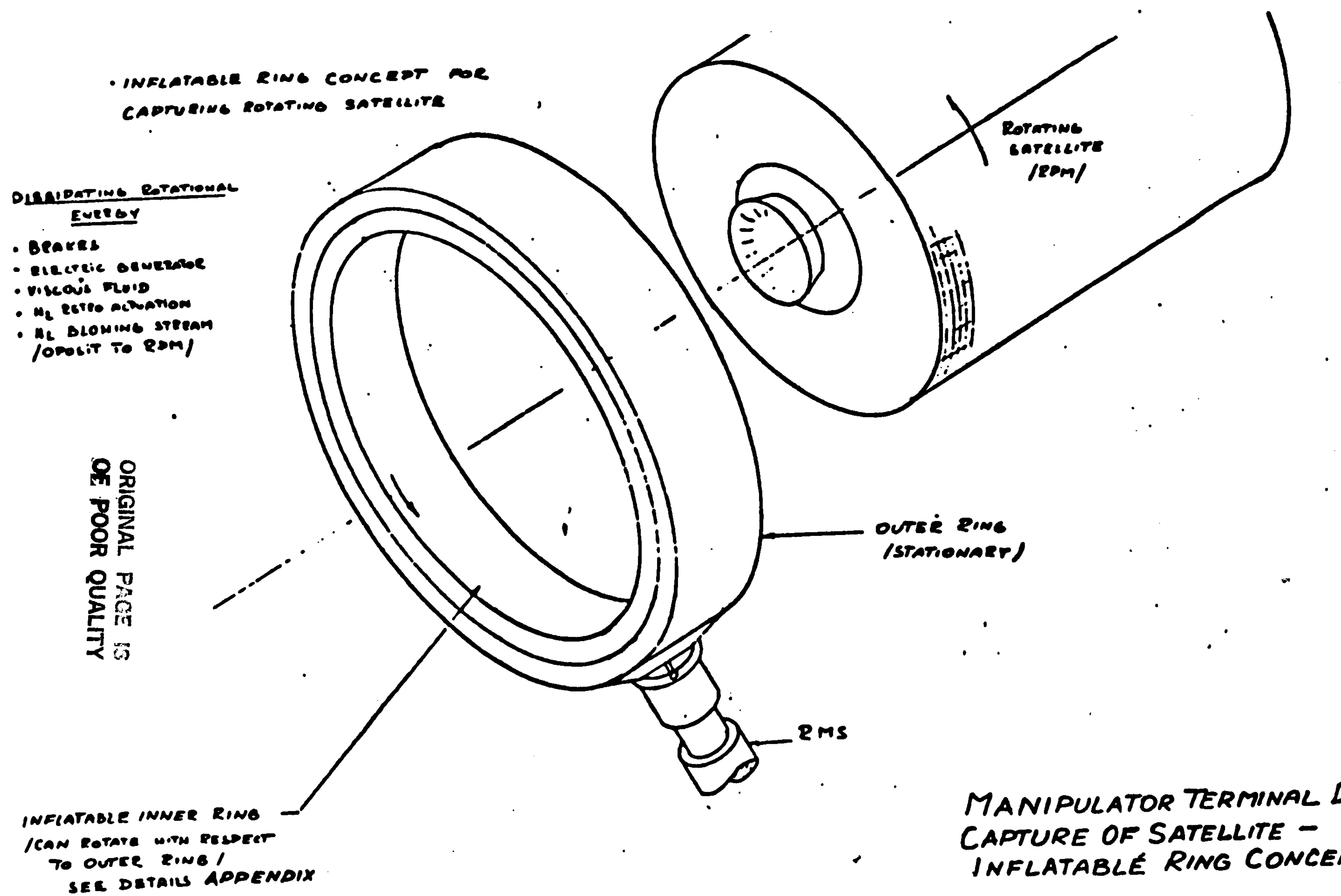
## SPECIFICATIONS:

- BLADDER OF MED 6600 ELASTOMER
- STIFFENING WIRES MOLDED INTO BLADDER FOR TORSIONAL RIGIDITY
- CENTRAL TELESCOPING STIFFENING MEMBER PROVIDES HANDLING RIGIDITY



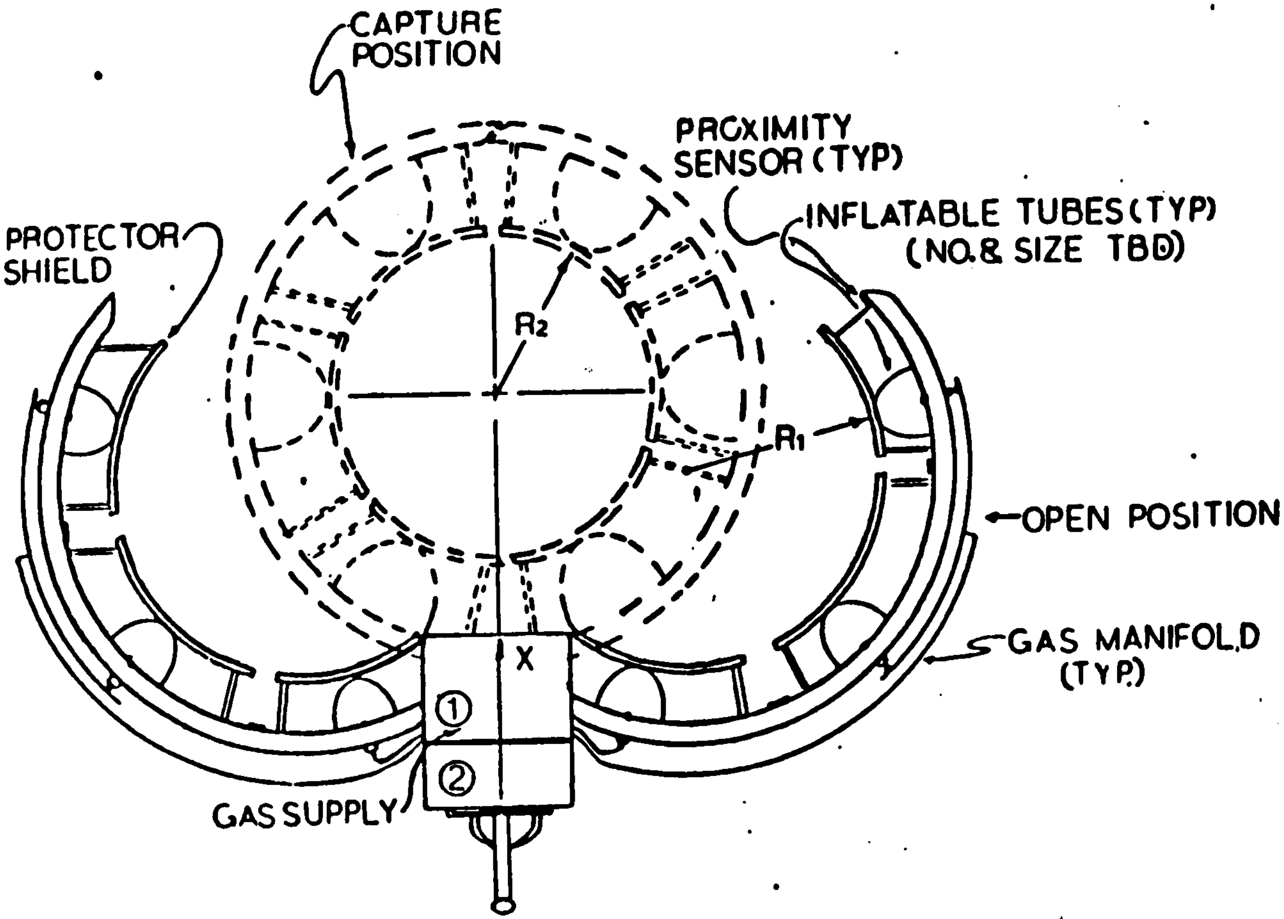
## ADVANTAGES:

1. WILL HANDLE MANY DIFFERENT CONFIGURATIONS OF HANDLING POINTS
2. REQUIRES ONLY ONE GRIPPING BLADDER
3. LARGE EXPANSION RATION PERMITS A LARGER POSITIONING ERROR




MANIPULATOR TERMINAL DEVICE
CAPTURE OF SATELLITE –
INFLATABLE RING CONCEPT

EE CONCEPT

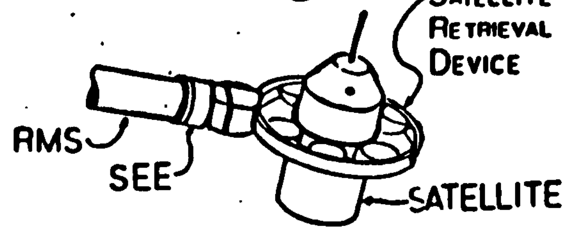



NOTES:

1) $R_1 > R_2$

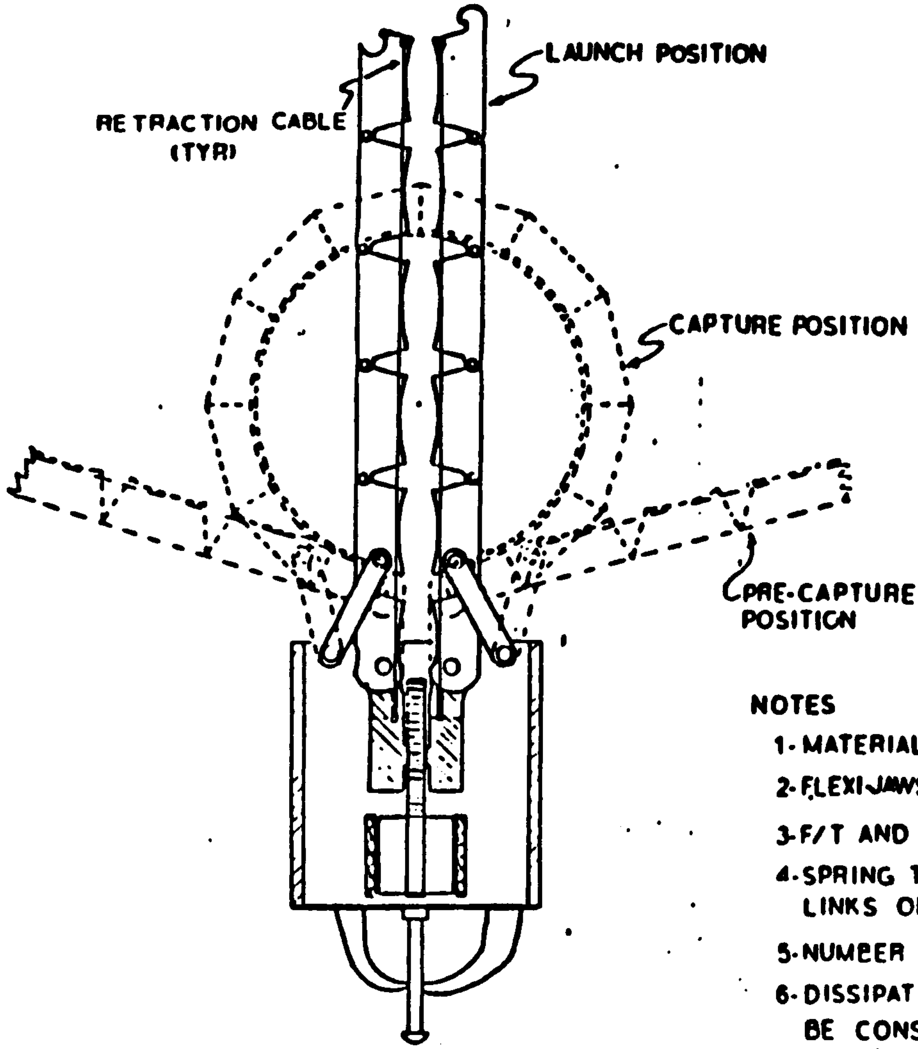
2) F/T SENSOR TO BE PROVIDED AT SEE

3) ITEM① CAN ROTATE ABOUT X AXIS. ITEM② CONTAIN BRAKE SYSTEM TO HALT ITEM①




4) BRUSHES (TBD) TO DISSIPATE THE ROTATION OF SATELLITE WILL BE CONSIDERD.

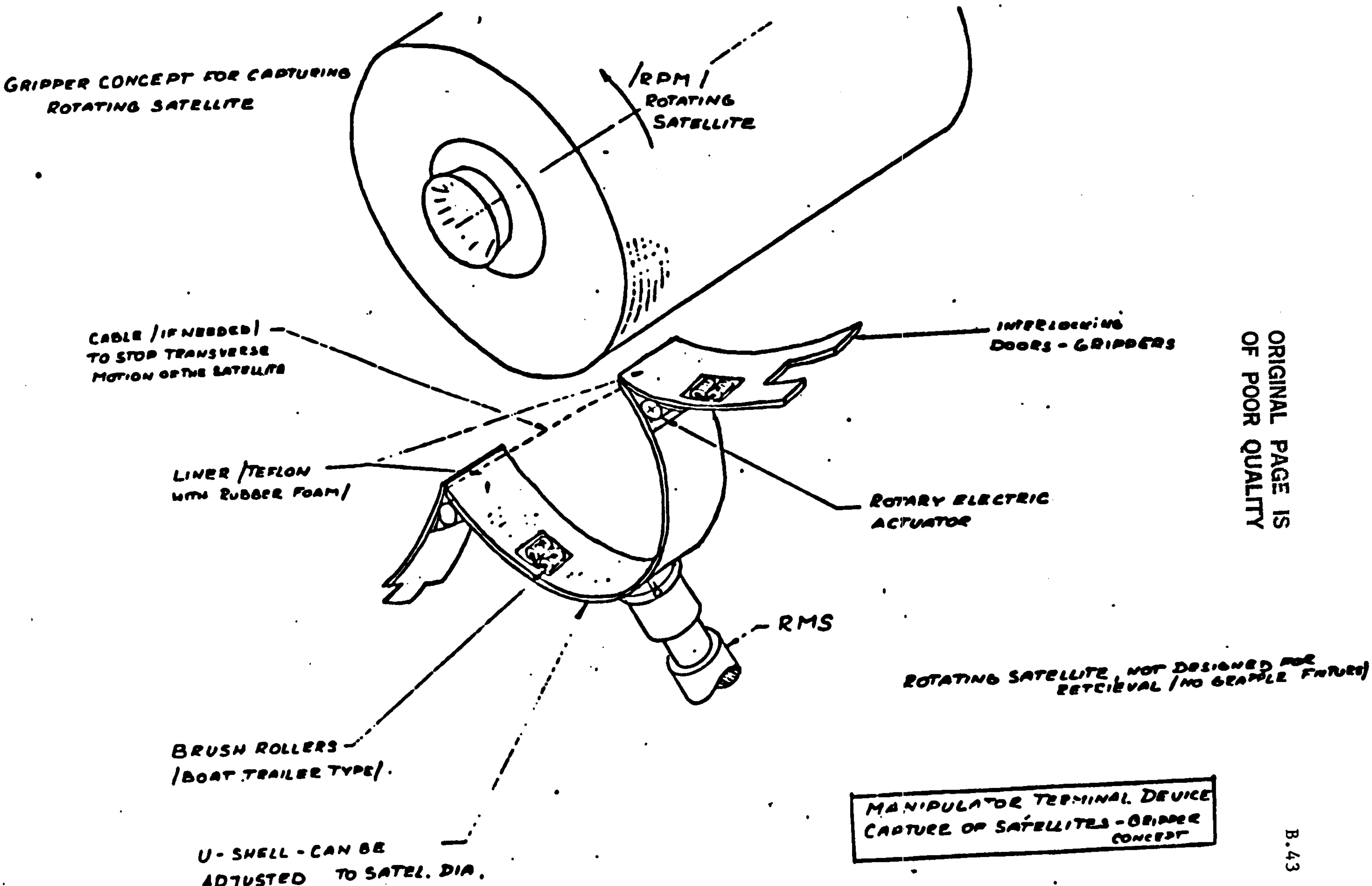
SATELLITE RETRIEVAL DEVICE CONCEPT.
(INFLATABLE TUBE)




NOTES

1- MATERIAL TO BE OF LOW DENSITY AND SOFT.
2- FLEXI-JAWS TO BE LINE REPLACEABLE ITEM.
3- F/T AND PROXIMITY SENSORS TO BE CONSIDERED.
4- SPRING TO BE INSTALLED AT EACH JOINT TO SET LINKS OPEN.
5- NUMBER AND SIZES OF LINKS TBD.
6- DISSIPATION OF ENERGY OF THE SATELLITE WILL BE CONSIDERD.

SATELLITE RETRIEVAL DEVICE CONCEPT




EE CONCEPT

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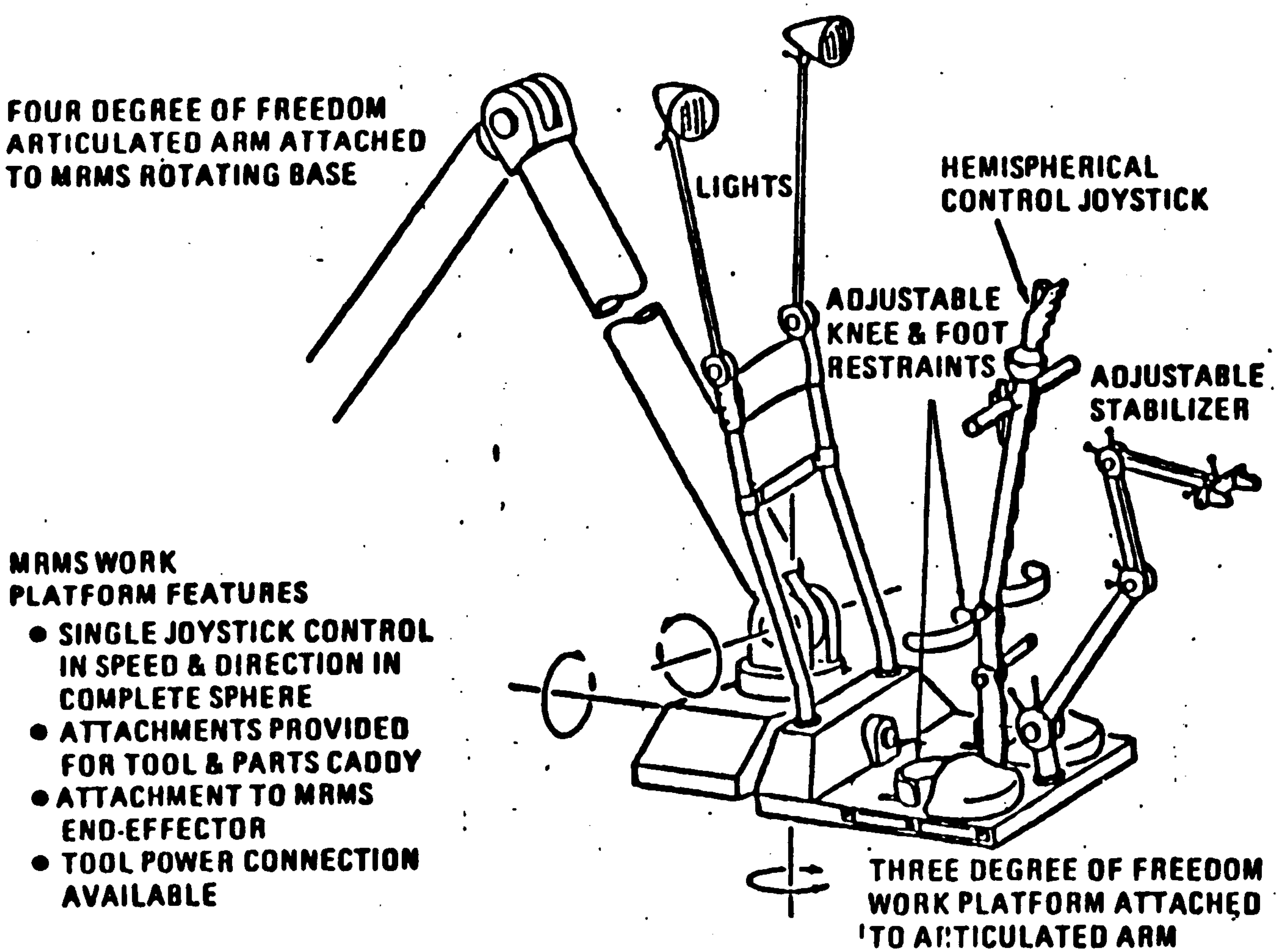
OF POOR QUALITY




MSC Work Station

# APPENDIX C

## REFERENCES AND INFORMATION SOURCES

A. ESA/ESTEC

1. Summary of ESTEC's technology work on end effector development by R. H. Bentall.

2. Charts from 1986 ESA presentation on Robotics, Telemanipulation, and servicing.

3. Grapple fixture requirements specifiction document No. TNO-3.5-86-EEDe.

B. NATIONAL SPACE DEVELOPMENT AGENCY OF JAPAN

1. Charts on JEM/RMS End Assembly Concept forwarded by Tak Kato.

C. JPL

1. End Effector pictures and engineering data on end effector systems developed at JPL, forwarded by Antal Bejczy.

2. Charts on "Study Proposals for Space Hands" presented at JCS by Bruno Jau on 3/21/86.

3. Draft report, dated 12/10/85, "Functional Requirements and Proposed Designs for Space-Based Multifunctional End Effector System" by A. H. Mishkin and B. M. Jau.

D. JSC

1. Charts from "Radiator Attachment Mechanism PDR", by W. D. Harwell, dated 1/1/686.

2. JSC-21000-HBK, STS Customer Accommodations," May 1986.

3. Charts from presentation of "Development of RMS as a Useful Tool," by M. L. Windler, 1/21/86.

4. Space Shuttle System Payload Accommodations, JSC-007700, Vol XIV, Rev G.

E. SPAR

1. RMS Standard End Effector Specifications [8/MSC 1986.1 (28/07/86)] forwarded by Andrew Jones.

2. SPAR documents; SPAR-RMS, R.089. issue C; SPAR -SG.366, issue E; SPAR -SG.377, issue B; SPAR-R.776 issue C.

F. LaRC

1. Charts on Mechanism Concepts and Control Requirements by Jim Wise.

2. Photos and Datas on LaRC's Parrallel End Effector and Quick Tool Change Apparatus from Jim Wise.

3. Data on Utah/MIT Dextrous Hand from Jack Pennington.

4. Data on Robot-Tech Systems, Inc. Versagrip III and MPMS Hand, from Jack Pennington and Jim Wise.

G. MSFC

1. Photographs and data on Marshall's End Effector studies forwarded by Don Scott.

H. SATELLITE SERVICING CATALOG NO. B1-104, DATED SEP 2983, TOOLS AND EQUIPMENT

I. LOCKHEED

1. LEMSCO-20924, "Component Survey for Enhancement of the Shuttle Remote Manipulator System."

2. LEMSCO-21012, "Feasibility Study of Manipulator Terminal Devices for Remote Manipulator System Enhancement."

3. Specifications and drawing for AKM Capture Device (ACD) Assembly for forwarded by Robin Hermes.

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The results of a study are presented for terminology definition, identification of functional requirements, technology assessment, and proposed end effector development strategies for the Space Station Program. The study is composed of a survey of available or under-developed end effector technology, identification of requirements from baselined Space Station documents, a comparative assessment of the match between technology and requirements, and recommended strategies for end effector development for the Space Station Program.

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