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AN OVERVIEW OF THE SHUTTLE REMOTE MANIPULATOR SYSTEM

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ABSTRACT

The development of the Shuttle Remote Manipulator System (SRMS) was the result of a cooperative program between the National Research Council of Canada, Spar Aerospace Limited (Prime Contractor) and NASA. The requirement to provide a six degree-of-freedom, remotely controlled manipulator for cargo deployment and retrieval during on-orbit operations of the Space Shuttle orbiter vehicle presented challenges in design, development, manufacture, test and program management, any one of which could be described in a paper in its own right.

This paper, however, presents an overview of the system requirements and performance of the SRMS, and provides data on some of the mechanical design considerations that were necessary during the development program.

The operational success of both the Orbiter and the SRMS during flights STS-2, -3 and -4 is ample evidence that the SRMS performed as expected and as desired.

While some minor improvements have been made in the follow-on production systems, one of which has been delivered and two are currently under construction, the system design has not changed significantly from that of the DDT&E hardware. Therefore, this paper is applicable to all four systems eventually to be operated by NASA.

PROGRAM DESCRIPTION

During the late 1960's, when the Apollo program was nearing completion, NASA approached the Government of Canada to determine if there was an interest by Canada in participating in the development of the Space Shuttle. Canada had an interest in remote manipulator systems, often referred to as teleoperators for operation in hostile environments such as underwater, nuclear power plant maintenance, arctic operations and mining. The National Research Council of Canada (NRCC) was selected as the government agency to interact with NASA. A memorandum of understanding was signed in July, 1975 between NASA and NRCC for the design, development, test and evaluation (DDT&E) of the SRMS. Spar and its industrial team members was chosen by NRCC as the prime contractor for the Canadian-funded DDT&E program. One of the more significant activities during the early design period (1975-1976) was to develop the system requirements, since there was no contract end item specification (CEI) in place. Spar and its subcontractors, DSMA ATCON (special ground handling and system test equipment), CAE Electronics Ltd., (display and control subsystem) and RCA Canada Ltd., (arm-based electronics) started work to define system requirements, subsystem specifications, statements of work and commence the control system design. Work proceeded towards a preliminary design review held in September, 1976, followed by a critical design review in April, 1978. Management of the program was controlled by Spar Aerospace Ltd. on behalf of NRCC, and a multi-agency Joint Review Board was set up to provide schedule review, program guidance, technical discussion and inter-agency coordination between NRCC, NASA (JSC, KSC, HQ), Rockwell International and Spar.

SYSTEM DESCRIPTION

System Requirements

The manipulator arm was to occupy a volume no larger than 50 ft. in length overall and having a 15 in. dynamic envelope. The overall system weight, including the display and control subsystem, closed-circuit television (CCTV), and manipulator controller interface unit (MCIU) was to be no more than 994 lb. The system was required to manoeuvre a "design case" payload of 32,000 lb. having dimensions 15 ft. in diameter and 60 ft. long. The maximum weight payload to be deployed (and retrieved in a contingency operation) was 65,000 lb. A significant design problem immediately encountered was to develop a servo control system which would be stable under all loaded and unloaded arm conditions where the moment of inertia varies by a factor of approximately 10^6. Further, a 32,000 lb. payload attached to the arm and translating at a velocity of 0.2 feet per second was required to be brought to rest within 2 feet. The unloaded arm had to achieve the same stopping distance criterion, but under a translational velocity of 2.0 f.p.s.

The initial design concept was a fail operational - fail safe system which required system redundancy, particularly in the joint motor drive. This resulted in a considerable weight penalty, and a decision was made in the early stages of the program to design a system that was fail safe only. This resulted in an overall system weight of approximately 950 lbs, or 44 lbs. under the specified control weight limit. Methods of redundancy, other than those requiring dual drive systems and dual electronics were incorporated.

The entire system has been designed to have a ten-year operational life, or the equivalent of 100 orbiter missions. Hence, considerable attention was paid to providing adequate margins in both the electrical-electronic and the mechanical systems. A mission, from an RMS standpoint, required the deployment and capture/berthing of up to 5 payloads.

System Configuration

Figure 1 shows the arm in diagrammatic form. It has a total of six degrees-of-freedom. A shoulder pitch and yaw joint, an elbow pitch joint and wrist pitch, yaw and roll joints. The shoulder and elbow joints are connected by a lightweight carbon composite boom approximately 13 in. in diameter and with a length of 16 ft. This is designated the upper arm boom. The lower arm boom, connecting the elbow joint output flange to the wrist forward electronics compartment, is 13 in. in diameter and approximately 19 ft. long. There are four major attachment points to the orbiter longeron; the main Manipulator Positioning Mechanism (MPM) for the arm is at the shoulder yaw pedestal, where a jettison system and cable cutter allows the arm to be separated from the orbiter in the event of a significant malfunction which would prevent stowage of the arm and closing of the payload bay doors. Three manipulator retention latch mechanisms (MRLs) support the arm at the elbow, wrist pitch and wrist roll electronics compartments. The MPM and MRLs roll inboard to allow payload bay doors to close. Further, the MRLs exert a force of about 2000 lb. on each latch roller on the arm, thus holding the arm firmly in position during launch.

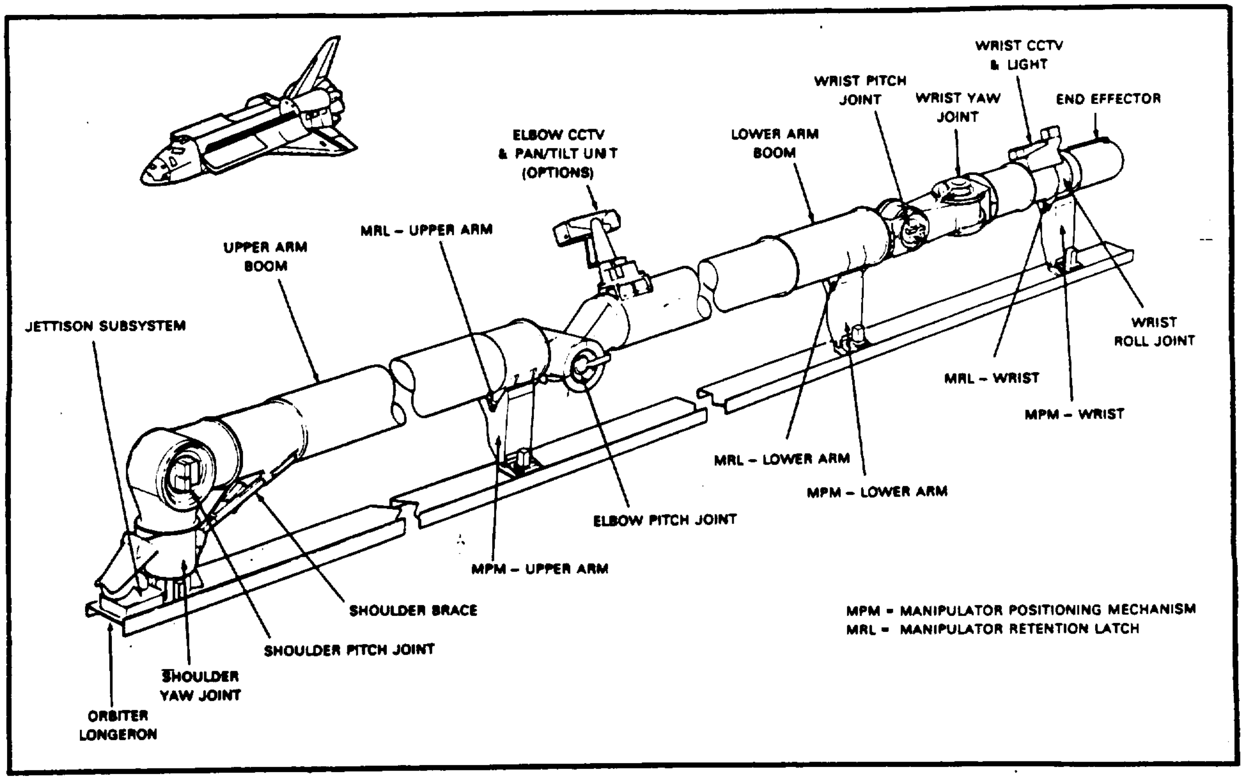

Figure 1 Manipulator Arm Configuration

Two CCTV cameras are located on the arm. The elbow camera has provision for pan, tilt and zoom and provides general payload bay, arm and payload viewing. The wrist camera is located on the wrist roll joint and rotates with that joint. Its purpose is to assist the mission specialist in manoeuvering the end of the arm (the end effector) over the payload-attached grapple fixture. The arm is covered over its entire length with a multi-layer insulation thermal blanket system which provides passive thermal control. This material consists of alternate layers of goldized Kapton, Dacron scrim cloth and a Beta cloth outer covering. The thermal blanket provides passive thermal control during most mission conditions, although during extreme cold case conditions, thermostatically controlled electric heaters (resistance elements) attached to critical mechanical and electronic hardware can be powered on.

The display and control subsystem provides the interface between the mission specialist and the RMS. Figure 2 shows the D&C panel and the translational and rotational hand controllers. The translational hand controller provides X, Y and Z translation at the tip of the arm, while the rotational hand controller provides pitch, yaw and roll commands, and is used primarily to manoeuvre the wrist joint. The D&C panel provides caution and warning information, mode of operation and arm health and status, commanded and actually achieved rates, digital readout information of individual joint angles or the end effector position in relation to a chosen coordinate system. Selection can also be made of various operating modes, automatic sequences and end effector operations.

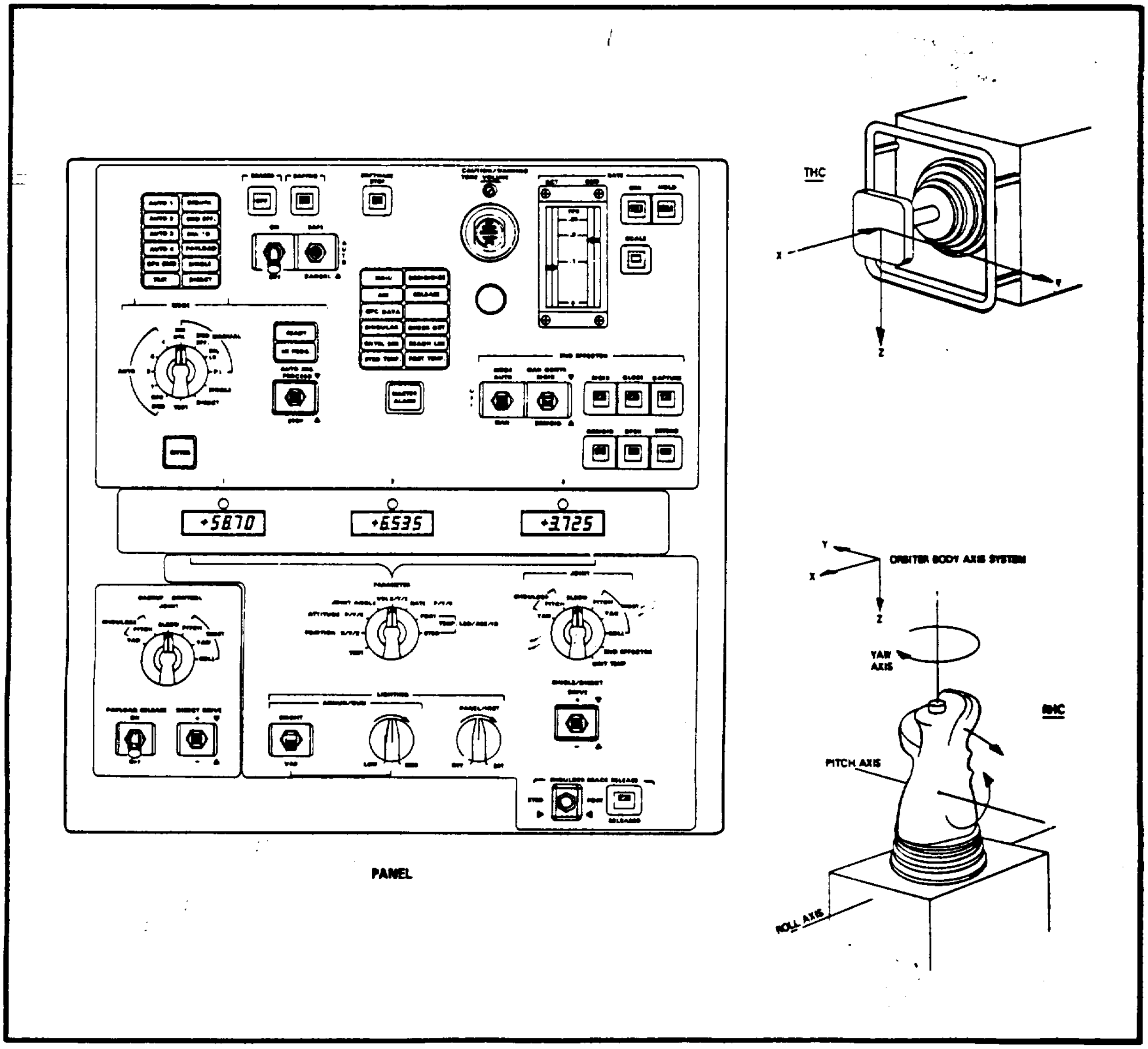

Figure 2 Display and Control Panel, and Hand Controllers

Electrical Subsystem

A block diagram of the electrical subsystem is shown in Figure 3. The interface between the orbiter general purpose computer (GPC) and the manipulator arm is via the Manipulator Controller Interface Unit (MCIU). Hand controller signals from the translational and rotational hand controllers are fed to the MCIU which then routes these commands to the GPC. The GPC provides reformatted commands back to the arm via the MCIU. A serial digital data bus routes commanded rates to the arm based electronics servo power amplifiers (SPA) which provide drive power to the joint motors. The GPC communicates with the MCIU every 80 ms, exchanging command and response data in this time frame. The MCIU also provides automatic safety features to protect the arm under certain operating conditions.

The software which controls the arm is resident in the GPC. There are ten software modules which perform command calculations, interface with the THC and RHC commands, provide drives for flags, meters and other annunciators, actuate the digital displays and provide caution and warning information. In the automatic mode of operation the GPC provides four preprogrammed automatic end-of-arm trajectories. Keyboard access also provides additional operator-derived automatic sequences which, when loaded in the computer, command the tip of the arm to move in a predefined trajectory.

There are six servo power amplifiers, one per joint servo motor. The shoulder electronics compartment contains two SPAs for the shoulder pitch and yaw joints plus a Joint Power Conditioner (JPC) essentially a DC-to-DC converter which supplies the various secondary bus voltages needed by the shoulder and elbow SPAs; a Backup Drive Amplifier (BDA) is also located in this compartment. The BDA is a replica (in part) of the servo power amplifier, but is used to command one joint at a time via a toggle switch on the D&C panel when the system is operated in the backup mode during contingency operations. The elbow electronics compartment contains a single SPA to drive its joint motor, while the wrist forward compartment houses the pitch and yaw SPAs and a single JPC; the wrist roll electronics compartment contains the SPA for that joint motor.

The arm is supplied with 28 volts nominal DC power and the D&C panel is provided with both DC power and 400 Hz, 115-volt, single phase AC power for lighting. During operation, the SRMS requires a maximum of 1 kilowatt of 28 volt DC for drive power, and a maximum of 1050 watts DC power for thermal control. In addition, 150 VA of 115-volt, 400 Hz, AC power at a power factor of 0.75 is provided for lighting control of the edge-lit D&C panel.

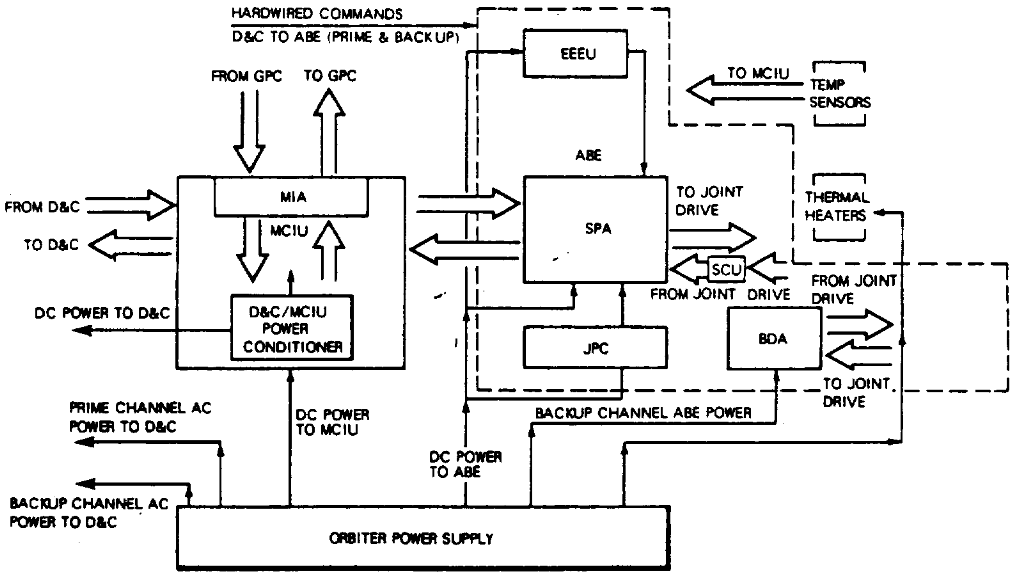

Figure 3 SRMS Electrical Subsystem Block Diagram

System Operating Modes

The SRMS can be switch-selected to operate in four standard modes. Three of these are supported by the GPC, that is, the commanded rate is fed to the joint SPAs via the serial data bus, and all joint operating commands to provide end point control of the RMS are carried out through calculations performed within the SRMS software resident in the orbiter GPC. The primary embodiment of this operating mode is in Manual Augmented. In this mode, the operator uses the two hand controllers to "fly" the end of the arm. Translational commands provided by the THC and rotational commands provided by the RHC are fed to the GPC via the MCIU whereupon the GPC performs a resolved rate algorithm calculation which provides serial control of each joint independently, although such joint-by-joint drive is not apparent to the operator. The servo system, shown in Figure 4, provides rate and position data at all times; two rate loops are used, an analog loop to maintain stability of the servo system itself, and a digital rate loops which is used to generate a rate error signal between the achieved and commanded rates.

Alternative modes of operation of the arm are available in (a) Single Joint control, wherein full GPC support is provided but the individual joints are controlled on a joint-by-joint basis, by applying a fixed drive signal to the control algorithms via a toggle switch on the D&C panel; this mode, rate commands are provided to drive the select joint while maintaining joint position control of unselected joints; (b) Direct Drive wherein the GPC is bypassed and a fixed rate command is supplied to the SPA motor drive amplifier summing junction via a toggle switch on the D&C panel and individual joints are driven on a joint-by-joint basis as selected on the D&C panel; (c) Automatic mode of operation, where the hand controllers are not used, all commands being generated by the GPC itself based on prestored or operator commanded (keyboard entry) auto sequence programs. Up to four preprogrammed auto trajectories may be selected using a selector switch on the D&C panel. GPC stored control algorithms output joint rate demands to obtain the required end effector position.

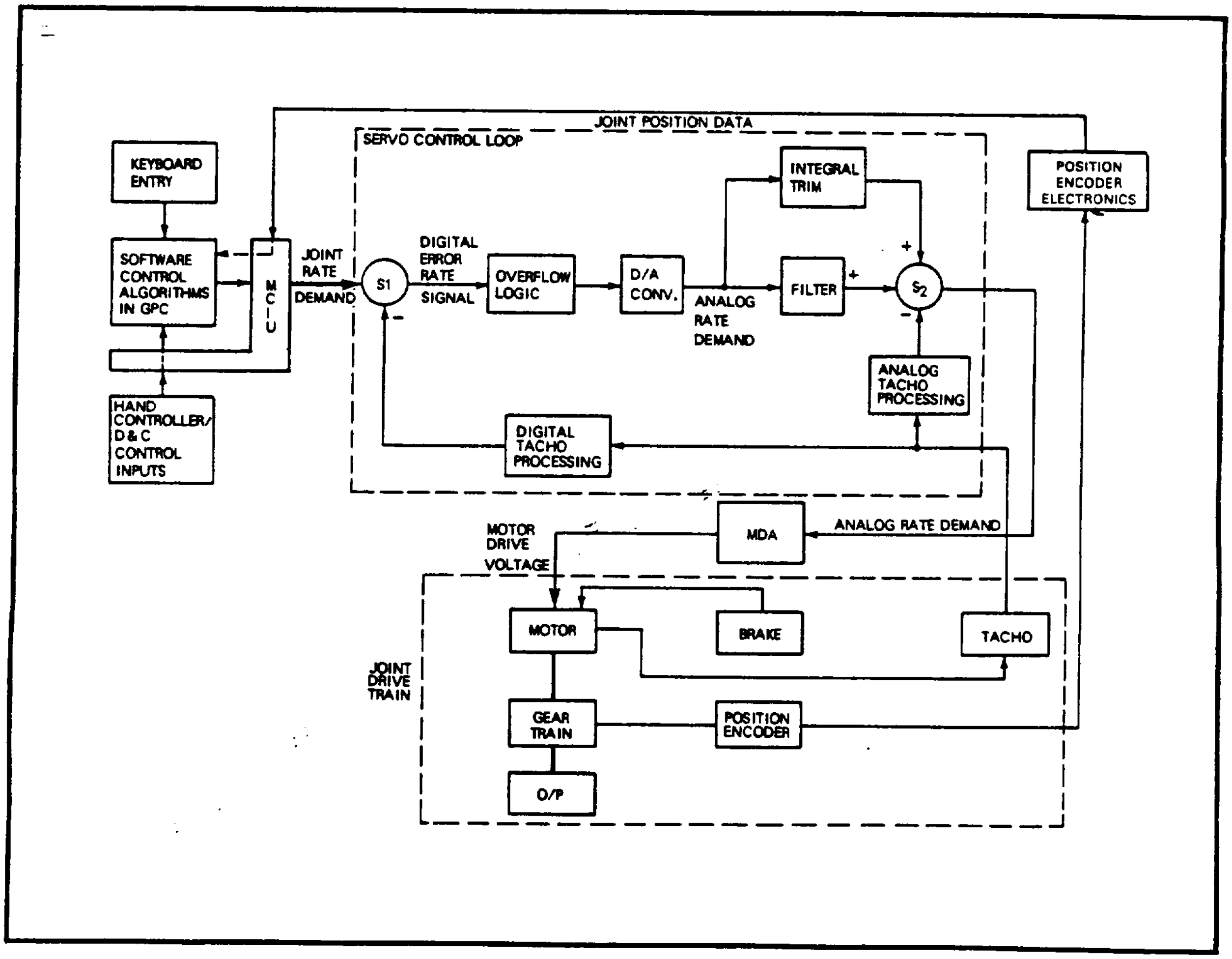

Figure 4 System Block Diagrm - Typical Joint

MECHANICAL CONSIDERATIONS

Joint Design

Each SRMS joint is powered by an optically commutated, brushless DC motor providing a stall torque capability of 100 oz/in and a no-load speed of approximately 90 radians per second. Dual commutator electronics are used to provide redundancy inthe sensitive area of the motor. Each motor is driven by an SPA which provides a pulse width modulated signal to the three motor windings. The command to the SPA via the serial data bus is a rate error signal, being the difference between the operator commanded rate and that rate fed back from the digital or low speed rate loop. The rate signals for feedback are obtained from an inductosyn tachometer mounted on the motor shaft. To obtain the high joint output torque needed from the relatively low motor torque available, an extremely high precision, high reduction gearbox with an epicyclic/planet system is used. Figures 5 and 6 show the joint motor and a cutaway of the shoulder pitch and yaw joints. The motor has its own internal gear train called the G1 which, through an output pinion, interfaces with the G2 of the main joint drive gear train system. All joints must be backdrivable; virtually zero backlash is demanded to maintain positioning accuracy and servo stability. Figures 7 and 8 show the general arrangement of the elbow and wrist joints. Dry type lubrication as opposed to the more traditional wet lubrication is used to maintain low friction and long lubricant life under the relatively low speed, high loading conditions experienced in the gearbox. Although these were mechanical design challenges presented early during the development phase, the gearbox has proven to be an extremely precise and trouble-free element of the overall design. A mechanical disc-type joint brake is provided as an integral part of the motor, and is used for maintaining the position of a joint during direct drive joint operation, and when the software-derived position hold mode is non-operative. Position information is obtained from an optical encoder with 16 bit resolution which provides precise joint angular position data. This is used as part of the overall joint control system, primarily when the arm is in the position hold mode as well as providing joint angular positions which are displayed by digital read-outs on the D&C panel.

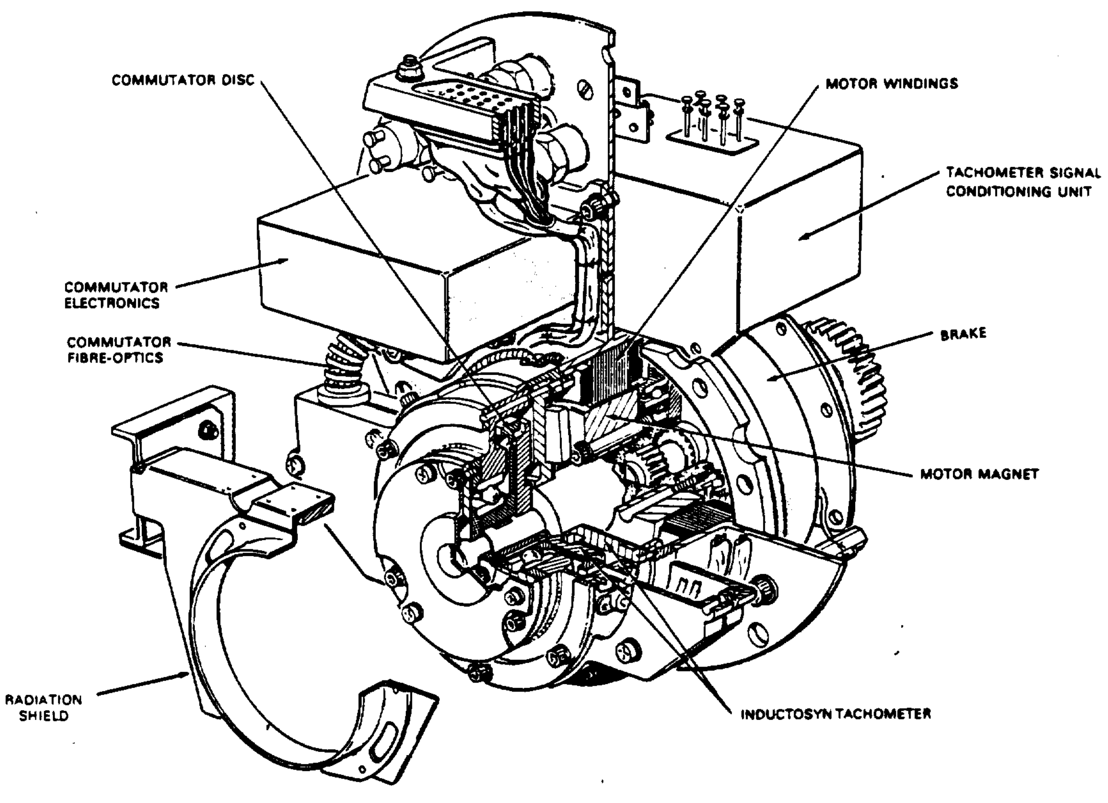

Figure 5 Motor Module Configuration

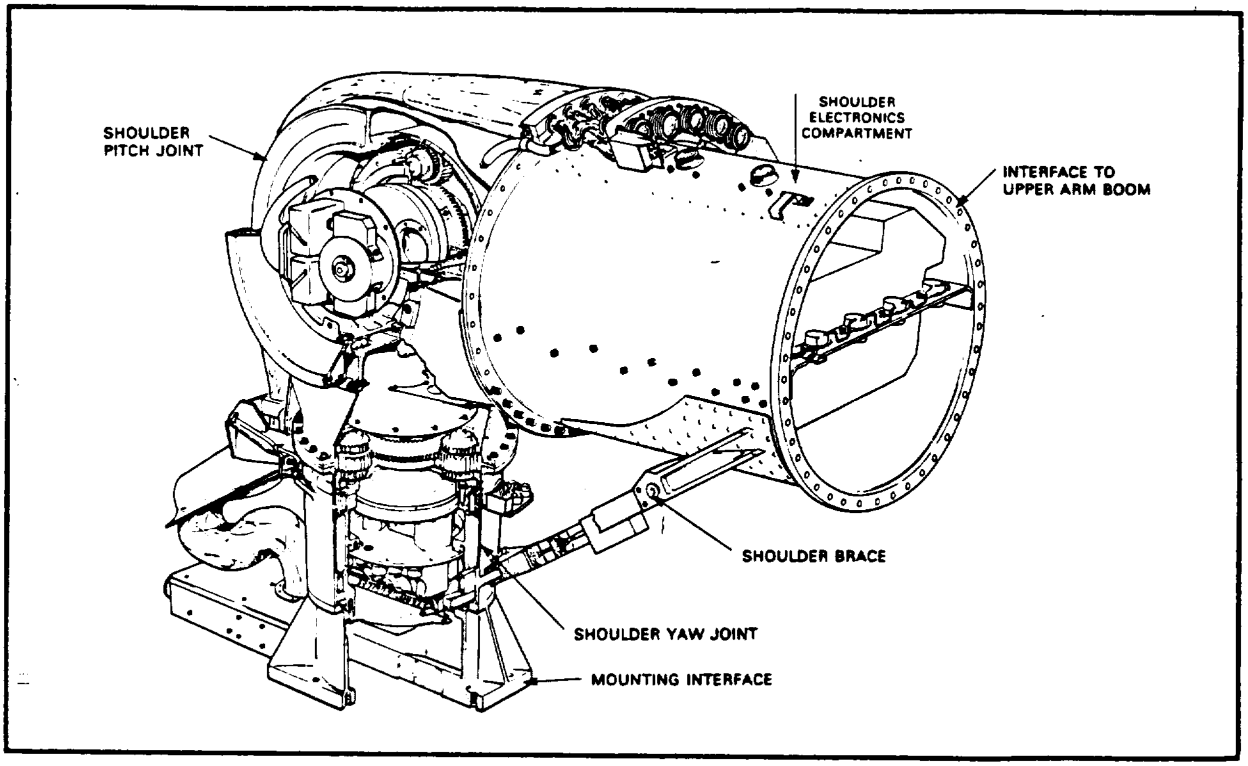

Figure 6 Overall Configuration of the Shoulder Joint

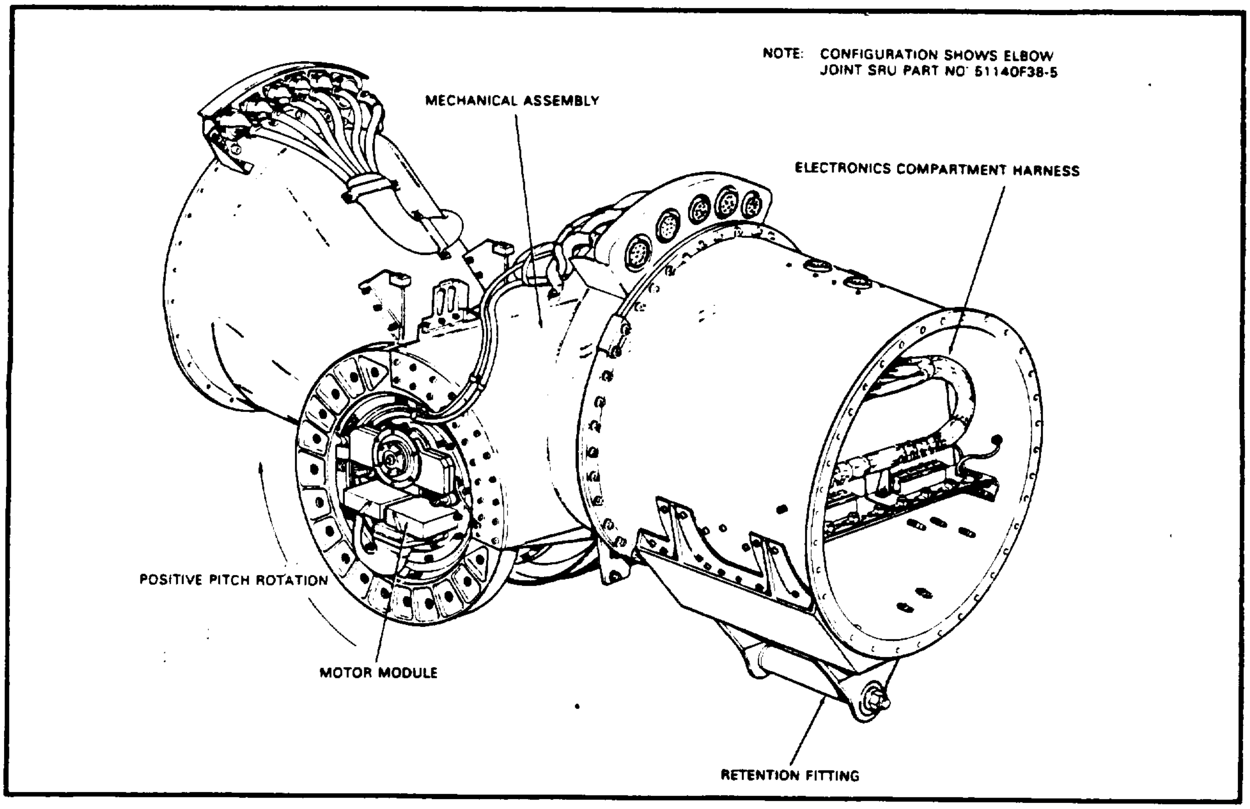
NOTE: CONFIGURATION SHOWS ELBOW JOINT SRU PART NO 51140F38-5

Figure 7 Overall Configuration of the Elbow Joint

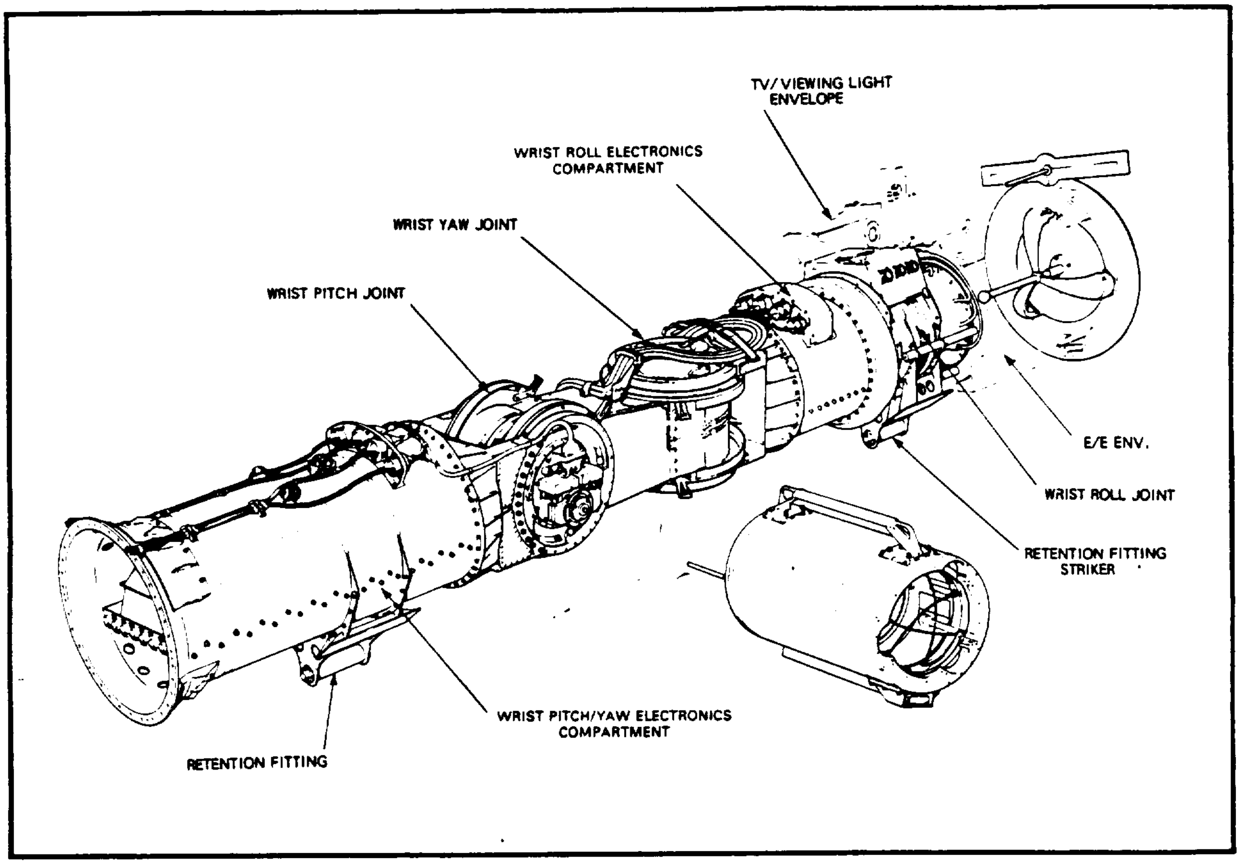

Figure 8 Overall Configuration of the Wrist Joint

Structural Considerations

Sturctural considerations during the design addressed the need to maintain adequate strength along the arm while minimizing arm weight. As a result, the output torques from each of the joints are graduated in descending order from the shoulder out to the wrist joint. Joint output torques and angular rotation limits are shown in Table 1 below.

TABLE 1

	Joint	Output Torque, ft-lbs	Maximum Angular Rotation, degrees
(a)	Shoulder Pitch	1,158	-2, +145
(b)	Shoulder Yaw	1,158	±180
(c)	Elbow Pitch	792	+2.4, -161
(d)	Wrist Pitch	347	±121.4
(e)	Wrist Yaw	347	±121.3
(f)	Wrist Roll	347	±447

Gear ratios for the various joints vary from 1,842 at the shoulder pitch and yaw to 739 at the wrist joints. The joints had to be backdriveable without damaging the gear train or overstressing the structure of any joint under conditions of a failed current limit circuit in the SPA. During dynamic braking conditions, the motor of each joint acts as a generator, and the electrical energy generated is dumped onto the DC bus. Normally the current so generated is limited, but should the current limit fail at maximum, the joints have to be able to withstand what essentially is a locked rotor condition.

The stiffness and weight distribution along the length of the arm has been optimized within the constraint of maintaining as great a commonality of parts as is possible, hence minimizing manufacturing costs and schedules. As a result, the stiffness in the wrist joint sections is somewhat less than the stiffness (and strength) in the shoulder joint area. The overall effect is to maintain an effectively tapered boom much like that seen in antenna tower supports. The joint structures, housings and gearboxes are designed with conventional materials such as 17-4PH and Custom 455 stainless steels, aluminum alloys of the A356, 7075-T7351 and 7050-T6 materials, and titanium alloys of the TI-6Al-4V category.

A balance of strength versus stiffness was needed in each of the joints. The shoulder joint, for example, is designed primarily for strength, generally to allow it to accommodate the failed current limit backdrive situation mentioned. The elbow and wrist are both a mixture of strength and stiffness designs. For example, the stiffness at the shoulder joint is 7.34x10^5 ft/lb per radian, while at the wrist joint it is 1.7x10^5 ft/lb per radian. The joint weights are 258, 117 and 186 lbs. for the shoulder, elbow and wrist, respectively. In some of the joints, fracture critical items require special non-destructive testing techniques to inspect for cracks. Hence, crack/flaw sizes are extremely small so that the 100 mission life can be achieved without significant crack propagation.

End Effector

The design of the end effector for the RMS was dictated by its main functional requirements:

- initial soft dock followed by rigidizing of the interface
- large capture envelope
  - 4 inch deep, 8 inch diameter cylinder
  - ±15° error in pitch, yaw and roll.

The configuration selected is shown in Figure 9 and its function is illustrated in Figure 10. It was selected in a trade-off with other types including internal and external claw-type, mainly because of its advantages in the two important areas mentioned as well as for its ability to provide a stiff load-path for handling heavy payloads. It is designed to be used in conjunction with special purpose end effectors (SPEEs) for the more intricate operations.

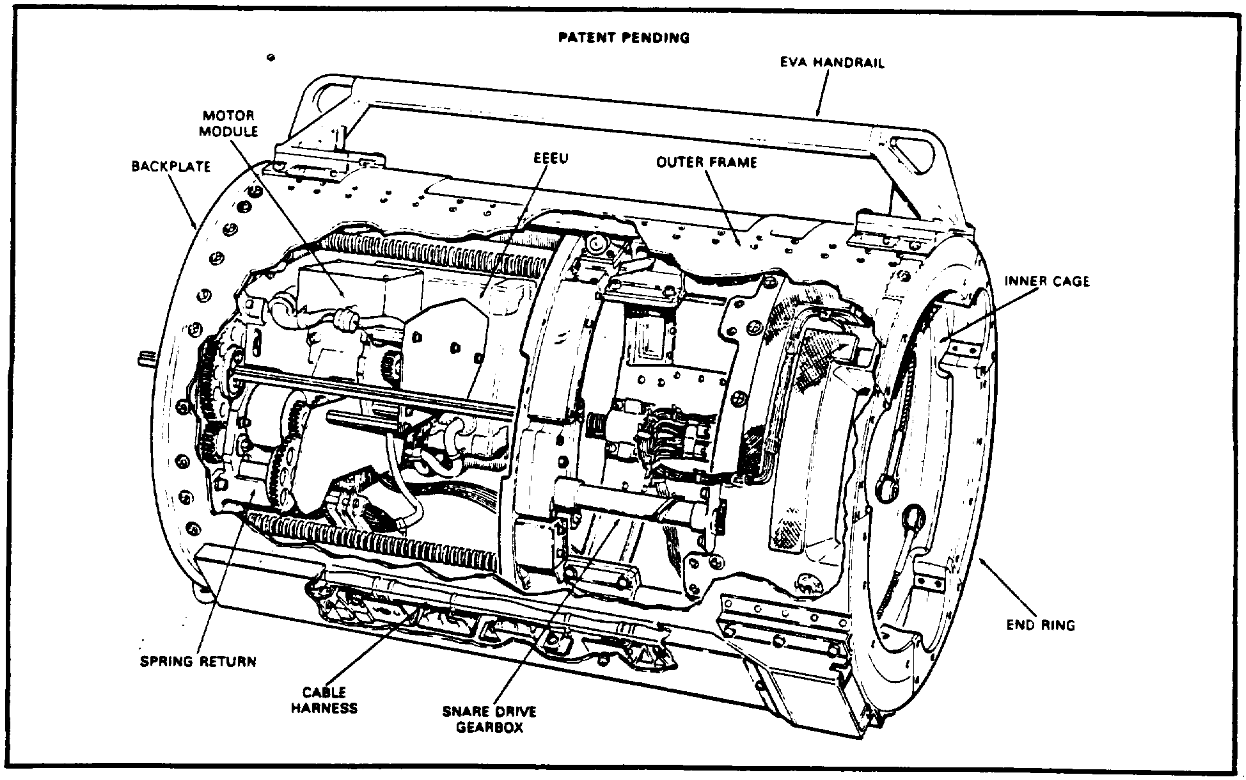

Figure 9 'End Effector Arrangement

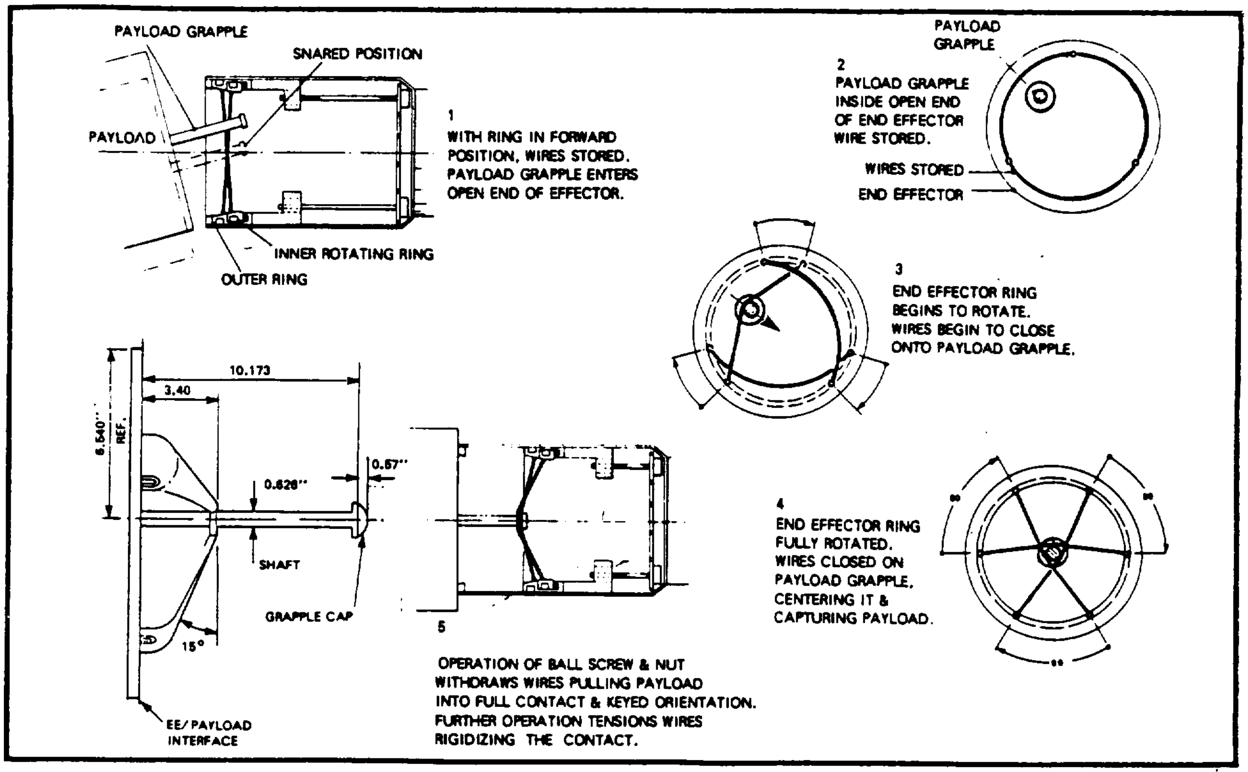

Figure 10 End Effector Capture and Rigidize Sequence

It functions by closing three snare wires around a pin attached to a payload so that the pin is centralized within the end effector. At this point the rigidization process starts when a ball-screw mechanism pulls the pin into the body of the end effector by means of the snares, thus bringing the alignment cams at the base of the pin into engagement with slots in the end effector. After these cams are mated, a preload force of 700 lbf is applied at the interface which provides the required stiffness for payload handling.

The device is thus a two-stage mechanism consisting of a large diameter snare drive ring and a mechanism for pulling this ring, and the snare cables, into the body of the end effector.

In the initial design, the end effector was to be an electrically redundant device whereby two electronic units drove a single motor coupled by clutches to the two drives. This was changed to simplify electrical interfaces and to save weight, so that the electronics drove both mechanisms as the primary drive but the redundant portion became a backup release system activated by a positive clutch release and driven by a negator spring motor.

End effector output forces and torques must be quite high while the inputs are current-limited and are therefore low torque systems amplified by gear boxes. This has meant that friction in the low torque systems has been a problem and a great deal of development effort has been devoted to solving this. Another problem has resulted from overestimating the capability of dry lubrication (LUBECO) in an axially-loaded bearing configuration. This led to the introduction of Braycote grease which has since been utilized in several applications in the end effector where high speed, moderately loaded bearings are used.

Arm Booms

The arm booms, constructed of graphite-epoxy, were designed and manufactured by General Dynamics of San Diego, to requirements specified by Spar. Figure 11 shows schematic details of the boom construction. Ultra high modulus GY/70/934 graphite epoxy was selected to meet the requirements of stiffness and strength within the boom weight limits. The upper boom uses 16 plys of 0.005" each oriented at 0, +38 and -38 degrees. The lower boom has 11 plys oriented in the same fashion. To maintain the stability of the thin-walled booms, intermediate stiffening rings are located internally at regular intervals along the length of each boom. The rings prevent the Brazier affect which can cause

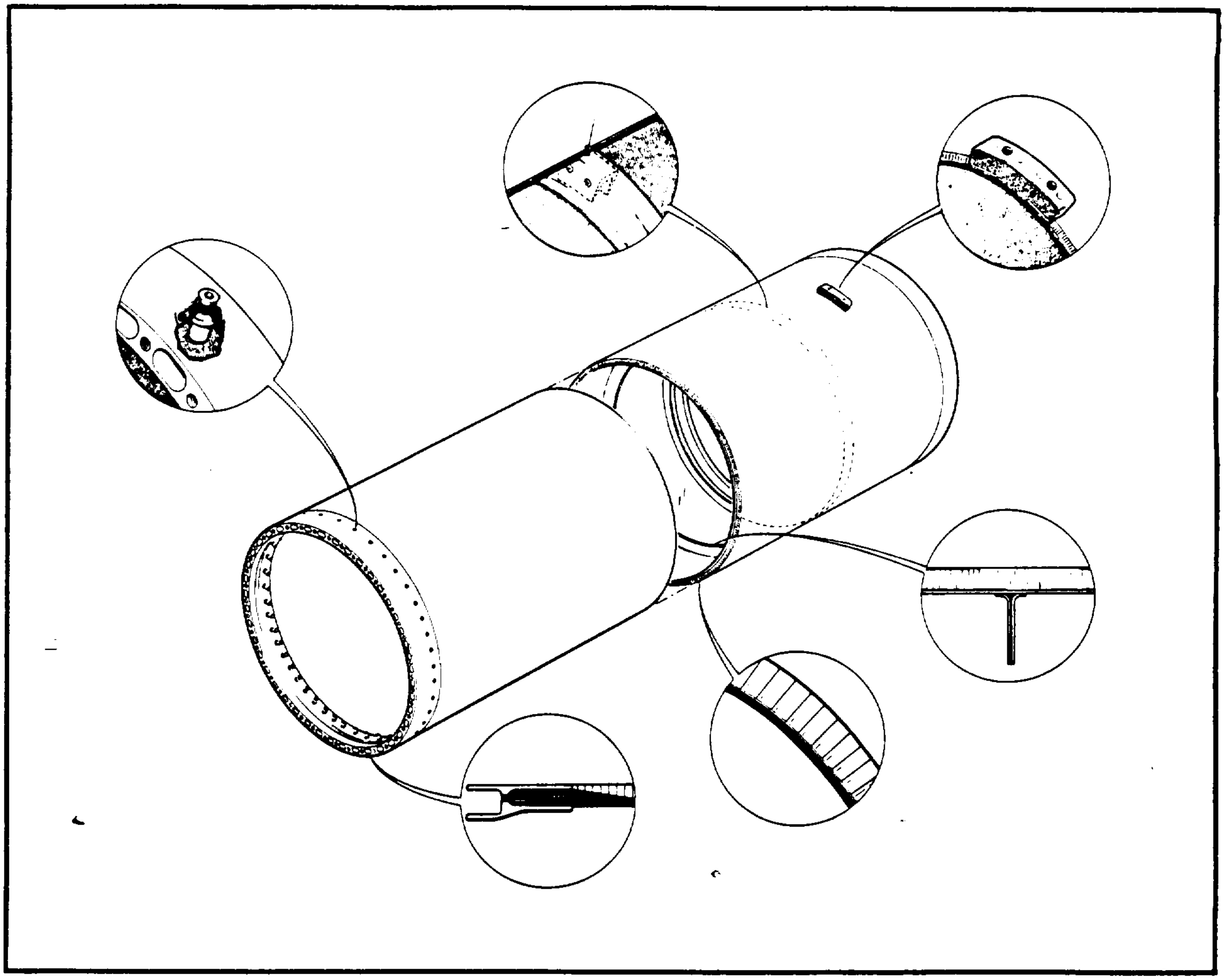

Figure 11 Arm Boom Construction

flattening of a thin-walled tube under bending, leading to premature collapse of the tube wall, and to increase the vibration frequency of the sidewall to well above the high energy acoustic range experienced during orbiter liftoff. Aluminum alloy (2124-T851) end rings are attached to the boom tubes at each end through a specially designed bolted joint. In this area, high strength T300/934 graphite/epoxy is used to increase the tube wall thickness locally for additional strength.

Because the booms are subject to damage from impact, a special bumper system is provided. The bumper system comprises precrushed HR-10 Nomex honeycomb bonded to a one-ply 102 Kevlar fabric skin bonded to the graphite/epoxy tube. The bumper system absorbs energy of up to 5 ft-lbs without indenting the bumper material. An impact of higher energy leaves a visible indentation on the bumper as an indication of possible local boom damage, requiring a local cutaway of the bumper material and visual or acoustic inspection of the graphite/expoxy subsurface. As a result of the combined stiffnesses of the individual joints and the arm booms, the unloaded arm provides the highest natural frequency of approximately 0.35 Hz in a straight arm configuration, and 0.027 Hz with a 32K payload attached.

SYSTEM PERFORMANCE SUMMARY

The on-orbit performance of the SRMS has met or exceeded expections. The data taken from the unloaded and loaded arm during flights 2, 3 and 4 when handling the PDP and the IECM show excellent agreement with the predictions of control system performance derived from both non-real-time and real-time computer simulations. Thermal performance was well controlled, and both hot and cold case on-orbit testing showed that arm based electronics and mechanical drive temperatures were held between 28 and 96 degrees F, worst case.

Because of the problems of testing a system on the ground which is intended to operate in zero-g, certain joint-related tests were run which showed that the major system requirements (forces, torques, joint stiffness), were met. An exception to this was the overall arm stiffness, originally specified at 10 lb/in in the straight arm configuration, and which actually was measured at 8.4 lb/in. The stiffness of the individual joints was within specification, hence the reduction in stiffness is attributed to the boom-to-joint interface stiffness not being as high as was thought necessary in the early phases of the design. This has been reflected in both real and non-real-time computer simulations and has not been identified as a problem, nor has it affected on-orbit operations.

Overall force at the end of a 50 feet straight arm was to be not less than 15 lbs and was achieved. Indeed, in some arm geometry configurations, considerable force can be exerted where mechanical advantages are greater.

Stopping distance, position hold accuracy of ±2 inch and ±1 degree, rate hold accuracy, overall operating envelope and all operating modes, including automatic safeing, (a feature that commands zero rates to all joints) and auto-braking under conditions of uncommanded motion have all been successfully demonstrated. Qualification testing of the system has been conducted for life and environments equivalent to 100 missions.

Because of low signal levels existing in the inductosyn tachometer rate loop, there were concerns that radiated RF fields of 2 volts per metre over the frequency range 14 kHz to 10 GHz would cause joint instability. These were unfounded. Indeed, test frequencies at field strengths up to 20 V/m were shown to not degrade joint performance or stability. Conducted interference and susceptibility were also within specification.

The true test of a system such as this is the ease with which it performs its tasks on-orbit. While only lightweight payloads have been handled through STS-4 to date, (deployed, berthed and manoeuvred) the crew comments about arm behaviour, stability, predictability and ease of operation have all been highly complimentary.

The successful conclusion of this major Canada-NASA program was the completion of the Operational Readiness Review held in November, 1982, and, as the Space Transportation System continues regular operational service, the SRMS will form an important element of the new era of manned spaceflight.

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