

THE DESIGN AND DEVELOPMENT OF AN END EFFECTOR  
FOR THE SHUTTLE REMOTE MANIPULATOR SYSTEM

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ABSTRACT

This paper describes the design requirements, the design, and qualification and development test problems encountered on the Remote Manipulator End Effector. The constraints and interfaces with the arm, the Orbiter, and the payload are identified. The design solution to meet the requirements is a unique device that provides a soft-docking feature termed capture and a hard-docking feature termed rigidization.

INTRODUCTION

The Shuttle Remote Manipulator System (SRMS) is required to deploy payloads to and from the payload bay of the Orbiter. The SRMS consists of a 6-degree-of-freedom, 15.24-m (50-ft) long manipulator arm mounted on a longeron of the Orbiter. The arm, which comprises a shoulder, elbow, and wrist joint, is operated from the crew compartment. At the free end of the arm is located an end effector that interfaces with and captures a grapple fixture on the payload. The capture mechanism is a three-cable system that closes around the grapple fixture. Once capture is completed, rigidization consists of pulling the payload toward the end effector and achieving a rigid interface. The mechanism is fail-safe in that a single failure will not lead to crew hazard. A backup release system is incorporated into the design that will permit release of the payload in the event of a prime channel failure.

The end effector has been designed to perform the above functions within severe constraints:

- o Size:
  - Diameter: 0.34 m (13.5 in)
  - Length: 0.46 m (18 in)
- o Weight: 29.5 kg (65 lb)
- o Misalignment (end effector to payload):
  - Lateral:  $\pm 0.1$  m (4 in)
  - Axial: 0.1 m (4 in)

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- o Vibration: launch environment
- o Thermal: orbital environment

Several problems were encountered during the development and qualification program. These are described in this paper, as well as design changes implemented to overcome the problems and produce a qualified unit for future Space Transportation System flights.

#### SPECIFICATION REQUIREMENTS

The following are basic requirements defined by the user, NASA-Johnson Space Center, and those derived by Spar Aerospace Limited as a result of overall SRMS and subsystem concept and design evolution:

- o The standard end effector will be attached to the wrist of the manipulator arm and used primarily for grappling or releasing payloads and applying loads and/or motions to the payload.
- o Capability for ground change-out of end effectors is to be provided, as well as the ability for the standard end effector to interface on orbit with a special-purpose end effector. (Actuation of the electrical interface will be provided by the special-purpose end effector.)
- o The system will be fail-safe, with a single operational channel for payload grappling and release. The backup channel will provide payload release capability only.
- o When operated in conjunction with the SRMS manipulator arm, by the SRMS operator, the end effector will grapple a payload grapple fixture with both linear and angular misalignments (delineated later in this paper).
- o Should the end effector fail to acquire the grapple fixture for any reason, no alternate mating or hangup will result.
- o Release impulse to be imparted to the payload is limited to  $9.5 \times 10^{-6}$  N-m ( $7 \times 10^{-6}$  ft-lb) in the prime mode and 0.068 N-m (0.05 ft-lb) in the backup mode. No force is to be imparted to the grapple fixture during end effector withdrawal, after release.
- o A single, detachable EVA handhold is required on the outside of the end effector.

- o Grappling of a payload is to be carried out using a soft-docking feature to initially center out radial misalignment. This is to be followed with removal of axial misalignment. Angular payload-to-end-effector misalignment will be carried out against a limped arm; i.e., an arm that has low backdrive resistance in each joint, except wrist roll, which is active.
- o Load transfer capability between end effector and payload is to be as follows (assuming a rigid grapple fixture/payload):
  - No interface separation up to 474.5 N-m (350 ft-lb) cross-axis (pitch/yaw) bending moment
  - Interface angular separation up to 3° permitted with a cross-axis bending moment as large as 1,627 N-m (1,200 ft-lb)
  - Full torsional (roll) load transfer capability required (even with 3° separation) for roll moments as large as 949 N-m (700 ft-lb)
- o Postrigidization roll accuracy of  $\pm 0.4^\circ$  and pitch/yaw accuracy of  $\pm 0.15^\circ$  are to be assured between end effector axes and grapple fixture axes. Axes are to be positioned within  $\pm 0.0025$  m (0.1 in) in X, Y, and Z.
- o Bending and torsional stiffness will be greater than 7,864 N-m/° (5,800 ft-lb/°) and 3389.5 N-m (2,500 ft-lb/°), respectively, for maximum applied moments of 474.5 N-m (350 ft-lb).
- o Capture and rigidization times are to be less than 3 s and 20 s, respectively. Payload-to-Orbiter relative velocity at moment of capture may be as high as 0.031 m/s (0.1 ft/s) maximum.
- o Impact loads are defined by maximum relative velocity (payload to end effector) of 0.122 m/s (0.4 ft/s).
- o Sighting aids are required on the payload side of the interface. Also, special markings are required on the end effector surface.
- o Operating life will be 100 mission cycles (5 operations per mission cycle) with a useful life of 10 years. Mean time between failures must be 8,333 h.
- o Operational, acceptance, qualification, and survival temperatures to be tolerated are as defined in Table 1. Also defined are payload (grapple fixture) temperature extremes.
- o Maximum allowable electrical power is 125 W for operation and 88 W for heaters.

- o Key vibration and load environments are shown in Table 2.
- o Maximum mass of the end effector will be 29.5 kg (65 lb).
- o Two modes of operation are required:
  - Manual - operator-commanded capture, rigidization, derigidization, and release
  - Automatic - operator-commanded capture; automated rigidization
- o Status switch signals as defined in Table 3 are to be provided to the operator.

#### OVERALL DESIGN SUMMARY

The end effector, which was designed and developed to meet the specifications that have been outlined, is shown in Figure 1. The details of this mechanism will be described in the following sections. Figure 2 displays a schematic functional diagram of the end effector system. The end effector is designed to mate with a grapple fixture of the type shown in Figure 3, which also shows the target used to visually assist in the grappling operation. Figure 4 illustrates the capture envelope within the end effector. This figure also outlines the details of the allowable linear and angular misalignments as given by the specifications.

The capture and rigidization mechanisms within the end effector are actuated by a single dc-brushless-motor drive as shown in Figure 1. Clutches are used to separate the mechanisms, and brakes prevent unwanted rotation. In the event of a failure within the prime channel, the backup release motor (spring drive) is automatically actuated upon release of the backup clutch. Spur gearing is used to provide the required output torques, and both wet (Bray grease 3L-38RP) and dry (Lubeco 905) lubricants are used within the assembly. In general, wet lubricant is used in the small bearings and dry lubricant in other bearings, gears, ball screws, and ball spline.

#### CAPTURE MECHANISM

Prior to attempting a capture, the snare carriage is fully forward and the snare wires are stored within grooves in the fixed and rotating rings (Figure 5, views 1 and 2). The operator maneuvers the manipulator arm such that the payload grapple shaft (Figure 3) is within the capture envelope. The capture-clutch-and-rigidize brake is closed; the rigidize-clutch-and capture brake is open.

To capture a payload, the inner rotating ring is driven through an 80° angle (Figure 5, views 3 and 4) to close the snare wires over the grapple shaft. Snare-closed and payload-present switches give flat indications of a successful capture and, in an automatic sequence, would automatically initiate rigidization. The snare-closed switch is contacted at the end of snare travel, and the payload-present switch is actuated by the increased cable tension that occurs when the cable passes over a grapple shaft. In this case, movement of a spring in the cable end actuates the switch.

Torque is transmitted to the end effector rotating ring from the backplate, where the motor module is located, via a ball spline assembly. During the rigidization sequence, when the carriage is pulled toward the backplate, torque is maintained on the snare system as the ball spline shaft travels through the backplate into a protective cover provided in the wrist roll joint.

#### RIGIDIZATION MECHANISM

Following a successful capture, the capture-clutch-and-rigidize brake is opened, and the rigidize-clutch-and-capture brake is closed. Motor torque acts through a spur gear train to three ball screws, the ball nuts of which are attached to the carriage. The ball nuts travel axially toward the backplate, along the ball screws, to effect the rigidization sequence. At the commencement of carriage travel, a flag on the D&C panel shows that carriage movement has started. The carriage travel continues until all misalignments have been pulled out and the grapple fixture baseplate is flush against the end effector end ring. At this point, a zero-tension flag is actuated on the D&C panel. (To release a payload, the snare wires are opened at this carriage position.) Continued carriage travel [approximately 0.025 m (1 in)] is required to fully rigidize the payload. A rigidize flag is activated at approximately 3,560 N (800 lb) of load in the grapple fixture probe. Since the rigidize flag (carriage position actuated) is adjusted to be actuated at a specific grapple fixture pull load, its sensitivity to changes in position as a result of temperature fluctuations required compensation. To this end, a Belleville spring system, preloaded 2,670 N (600 lb) to 3,114 N (700 lb), was installed (Figure 1) in the carriage between the ball screw nuts and the snare ring assembly, and the rigidize switch is adjusted to actuate within the Belleville system's range of travel. Thermal vacuum testing has confirmed that between high- and low-temperature limits, the rigidize switch is contacted within the grapple pin load range of 3,290 N (740 lb) to 3,650 N (820 lb).

## BACKUP RELEASE MECHANISM

A spring motor is located on the backplate, near the motor module, to provide backup release capability. Testing has confirmed that this system will open the snare wires at any carriage position from fully rigidized to fully forward. A schematic of the end effector drive mechanisms including backup release is shown in Figure 6.

The spring motor is connected to the motor drive via spur gearing and a backup dog-tooth-type clutch. During normal operation, the negator spring is continuously wound and unwound between its two spools (Figure 1) as the snare system is opened and closed. In the snare-closed position, the spring (which is backwound on the drive spool) provides a constant torque of approximately 70.6 mN-m (10 oz-in) to open the snare system, when the backup clutch is opened.

## DEVELOPMENT PROBLEMS AND SOLUTIONS

### Capture Mechanism - Main Bearing Thermal Compensation

The large 0.3-m (12-in) diameter ball bearing that supports the rotating ring is mounted into an aluminum structure. At cold temperature, the increase in bearing preload raised friction torques beyond the capability of the backup release mechanism to open the snare system. This was corrected by the provision of a looser bearing fit in the structure, but at the expense of slightly increased vibration wear at the snare drive output gearing because of the increased radial play. The provision of additional carriage or bearing support in the launch configuration is currently being reviewed.

### Rigidization Mechanism - Alignment

Development testing demonstrated the need, in this design, for precise relative alignment of the three ball screws, the ball spline, the rigidization spring assemblies, and the carriage guide rollers. Close tolerance fixtures (Figure 7) were developed to meet this need.

### Lubrication

The end effector was originally lubricated with Lubeco 905 dry lubricant throughout. However, certain bearings, which were required to accelerate very rapidly to high speed (e.g., approximately 7,000 r/min in 1 s), failed due to clogging with dry-lubricant debris. A design change to wet lubricant (Braycote 3L-38RP) in these bearings has resulted in no further problems to date.

### Backup Release Spring Motor

Under certain rapid stop-start conditions, the spring would unwind from the drive spool faster than it could play onto the takeup spool. This resulted in failure of the system. Backwind roller restraints were added around the periphery of each spool to act as low-friction devices to contain the spring within each spool. Satisfactory performance of the spring motor resulted from this modification.

### Motor Modules - Brakes and Clutches

During certain portions of the capture-and-rigidize cycle, the brakes and clutches are required to slip at their preset slip-torque values. Although these devices successfully completed a representative-life test program, friction pad wearout, with a resultant drop in slip torque below specified minimums, has been experienced after prolonged use. No design changes were incorporated to correct this problem, but the devices have been declared as life-limited items (50 missions).

### CONCLUSIONS

An innovative design for the capturing and docking of payloads has been produced that meets very severe envelope, loading, and environmental requirements. Problems that have occurred during the performance of development- and qualification-level environmental testing have been corrected, and the test program to formally qualify the design for the Orbiter mission is currently underway.

Several other areas of potential product improvement have been identified and are being evaluated for possible incorporation in follow-on production units. These items are:

- o Reduced vibration wear and damage to the rigidize-carriage guide tracks and snare-drive output gearing may be accomplished through improved support to these assemblies in the launch configuration (carriage fully forward). Design methods under consideration are:
  - Taper-fit support to the carriage and rotating ring at the carriage-to-housing interface
  - Carriage track bearings that are preloaded against the guide tracks to eliminate free play
  - Steel inserts in the aluminum guide tracks to provide increased tolerance to severe vibration loads

- O-ring-type support to the large 12-in carriage bearing at the housing and shaft interface; again, to eliminate free play
- o Increased use of wet lubrication may eliminate any risks related to bearing or mechanism clogging from debris generation. Research and development in this area is, in some instances, confirming the increased reliability of this approach.
- o Further, some specification changes related to force-moment and proximity sensing are under consideration and these, if approved, will undoubtedly result in mechanical design impact.

#### ACKNOWLEDGMENT

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Table 1. End Effector Temperature Limits (°C)

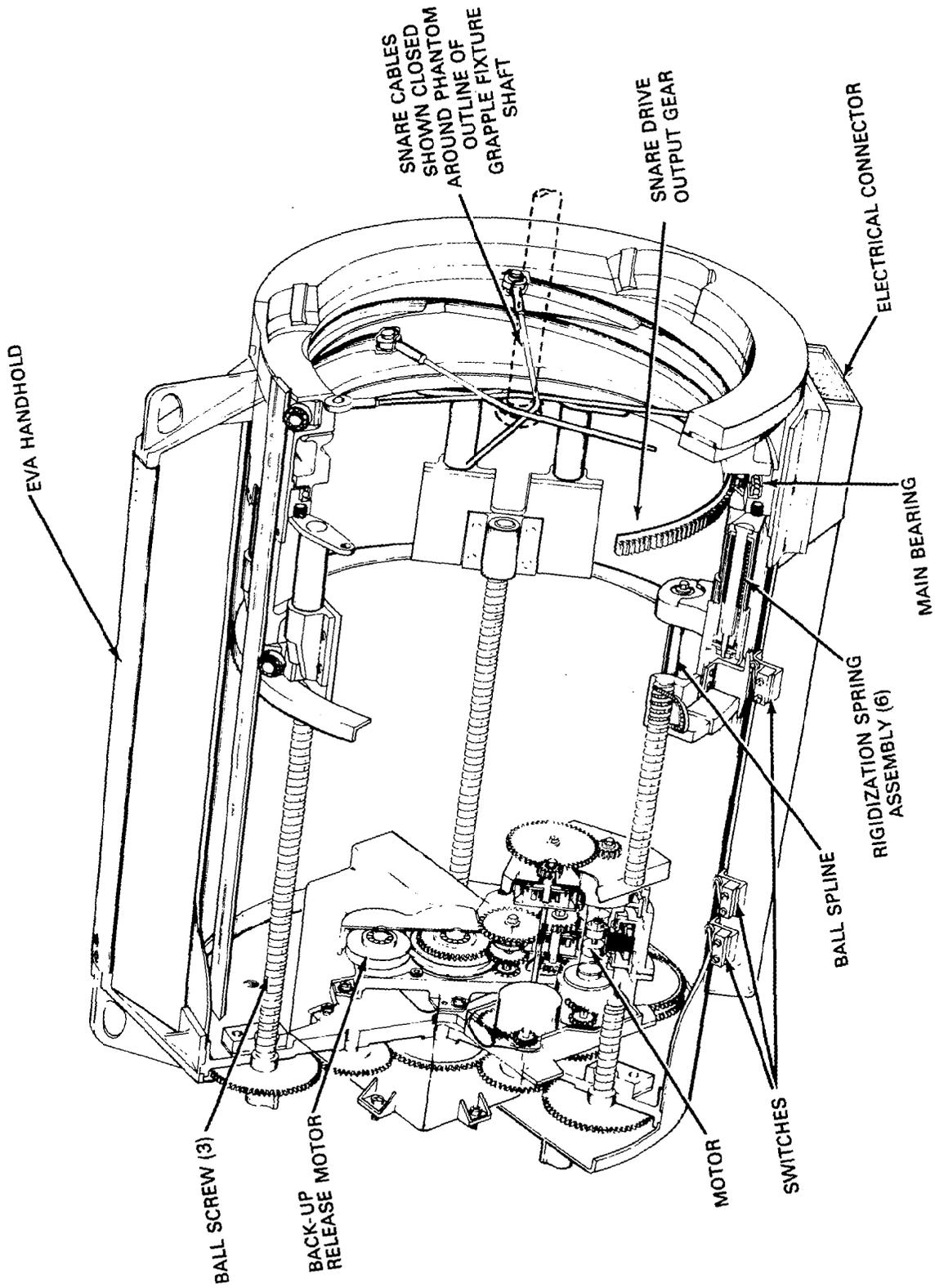
|                           | OPERATIONAL |      | ACCEPTANCE |      | QUALIFICATION |      | SURVIVAL |      |
|---------------------------|-------------|------|------------|------|---------------|------|----------|------|
|                           | MAX.        | MIN. | MAX.       | MIN. | MAX.          | MIN. | MAX.     | MIN. |
| ELECTRONICS UNIT          | 65          | -20  | 70         | -25  | 81            | -36  | 81       | -50  |
| MOTOR MODULE COMPONENTS   | 80          | -5   | 85         | -10  | 96            | -36  | 101      | -36  |
| EVA HANDHOLD              | 69          | -94  | 76         | -99  | N/A           | N/A  | N/A      | N/A  |
| PAYLOAD (GRAPPLE FIXTURE) | 121         | -156 |            |      |               |      |          |      |

Table 2. Key Loads and Environments

|                                      |   |
|--------------------------------------|---|
| MAXIMUM ACCELERATION (CRASH CASE)    | 9 g   |
| SHOCK                                | 20 g 11 ms  |
| RANDOM VIBRATION (HARD MOUNTED)      | 0.8 g <sup>2</sup> /Hz, 80 to 100 Hz                  |
| ARM OPERATION (INCLUDING RCS FIRING) | 1085 Nm (800 FT LB) BENDING, 515 Nm (380 FT LB) ROLL  |
| ARM BRAKING                          | 976 Nm (720 FT LB) BENDING, 651 Nm (480 FT LB) ROLL   |
| ARM JOINT LOCKED MOTOR               | 1627 Nm (1200 FT LB) BENDING, 949 Nm (700 FT LB) ROLL |

Table 3. Status Switch Signals

- |   |
|---|
| <ol style="list-style-type: none"> <li>1. SNARES OPEN</li> <li>2. SNARES CLOSED</li> <li>3. RIGIDIZATION COMPLETE</li> <li>4. END EFFECTOR DE-RIGIDIZED (ZERO TENSION)</li> <li>5. END EFFECTOR EXTEND</li> <li>6. PAYLOAD PRESENT</li> </ol> |
|---|



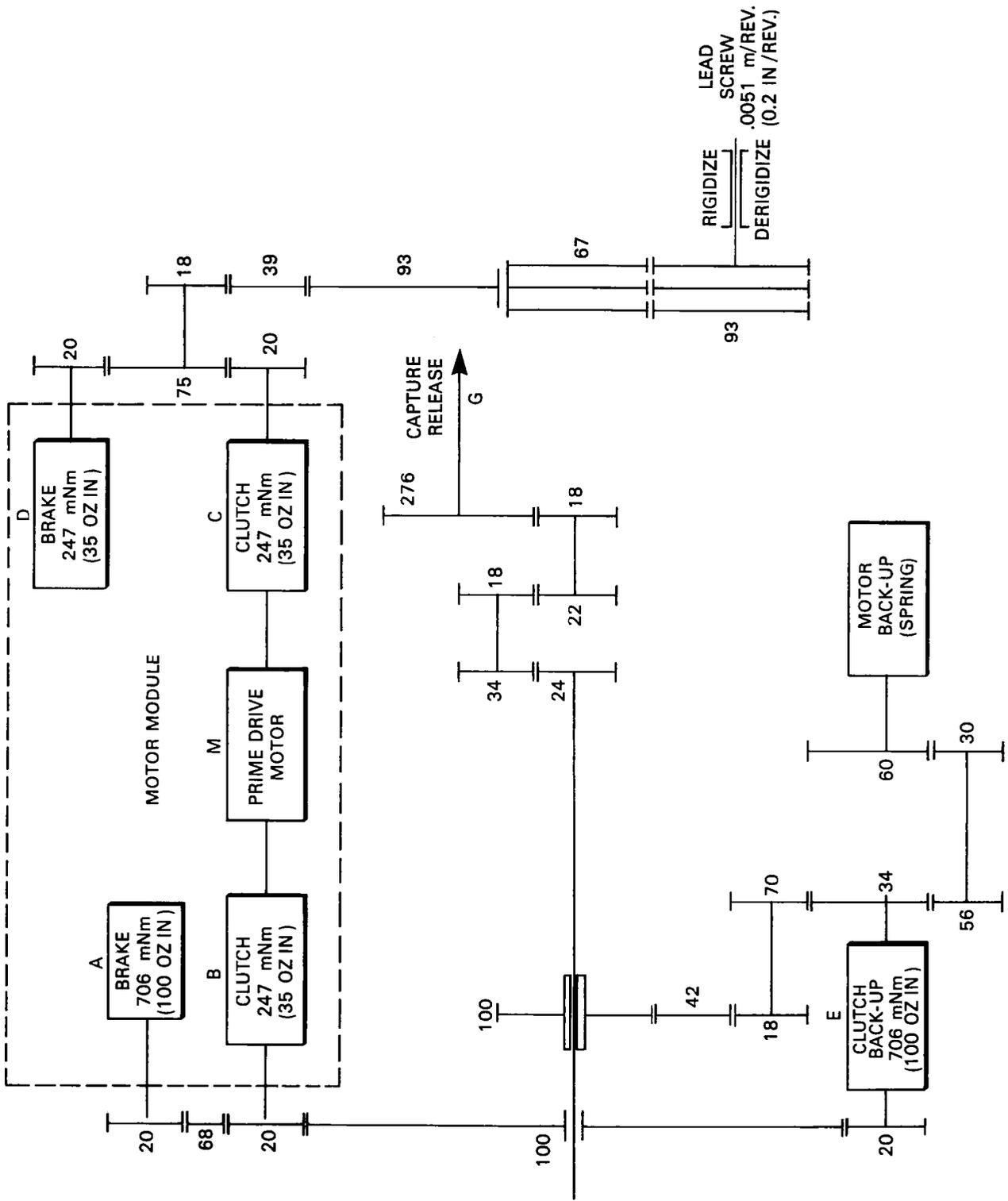


Figure 2. End Effector Schematic Functional System

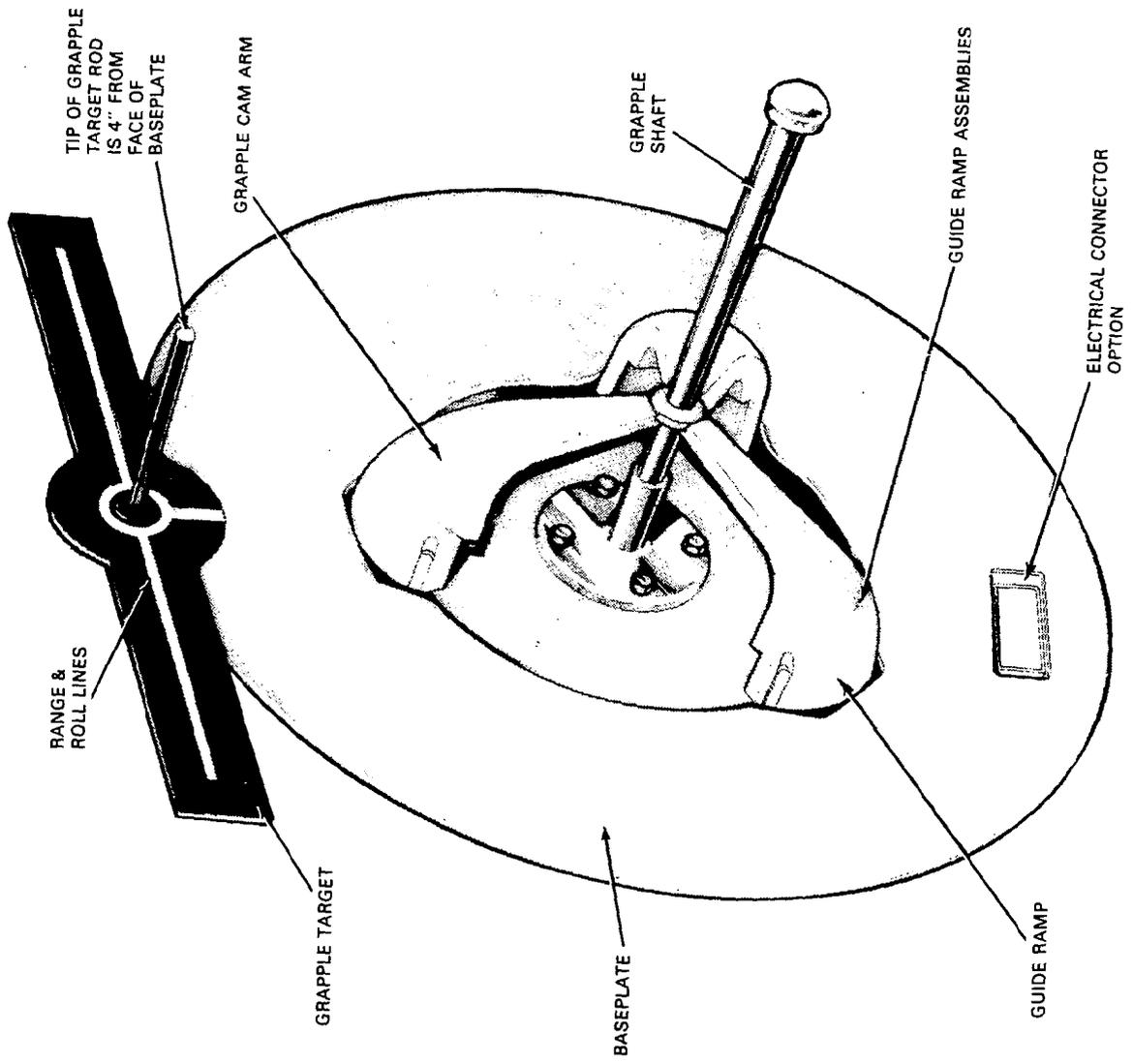


Figure 3. Grapple Fixture and Target Assembly

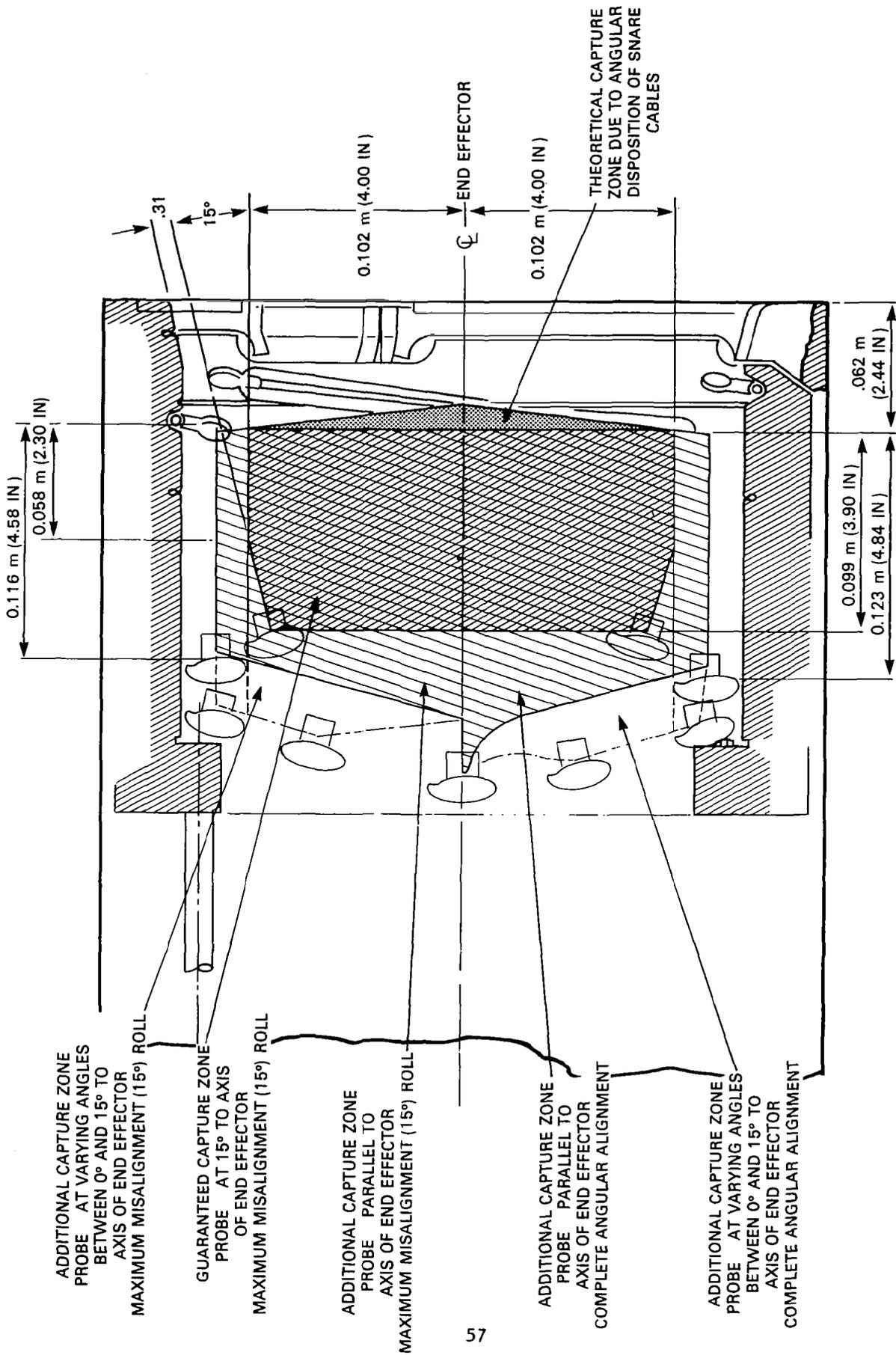


Figure 4. Capture Envelope - End Effector

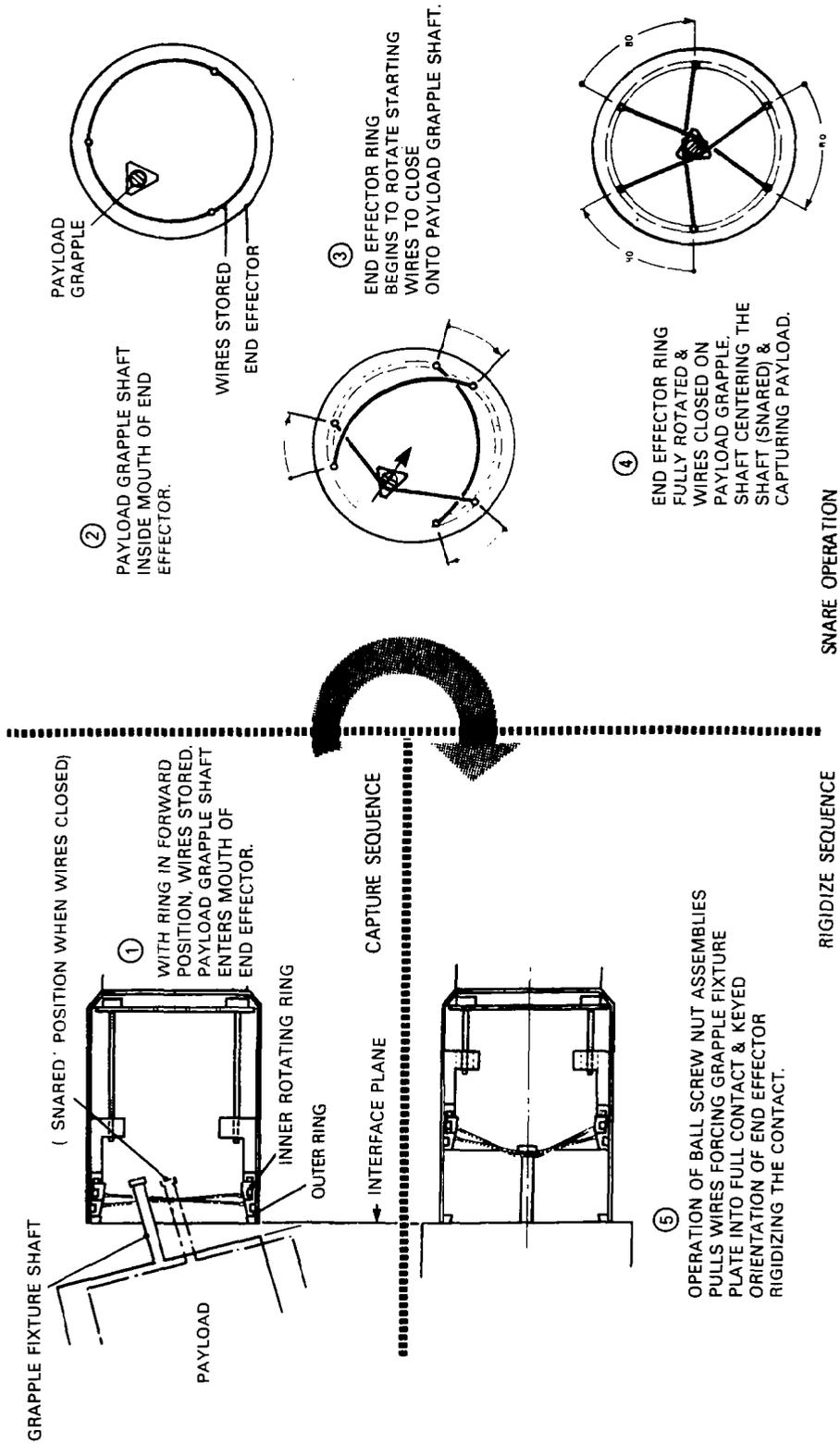


Figure 5. End Effector Operation

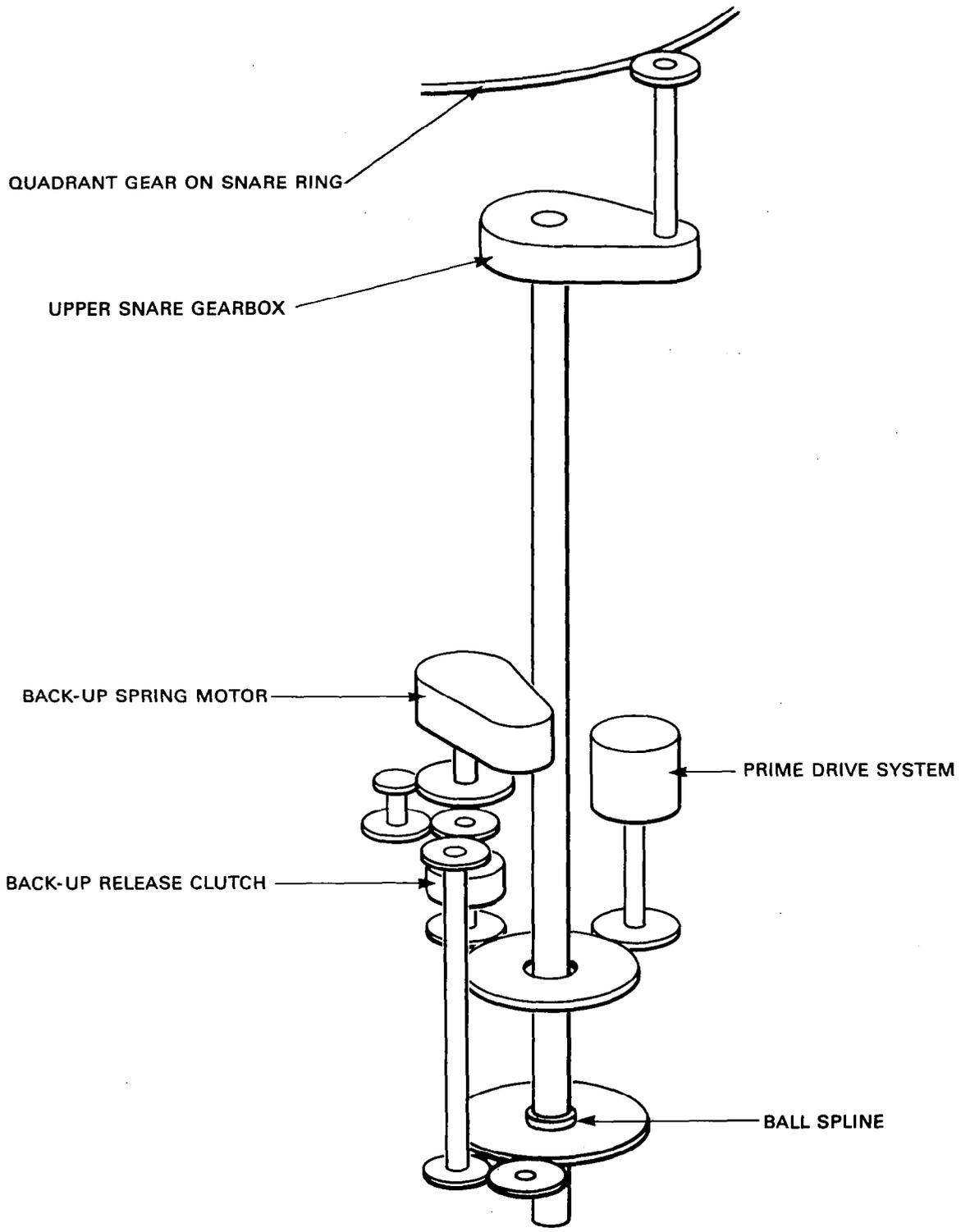


Figure 6. Schematic End Effector Backup Release System

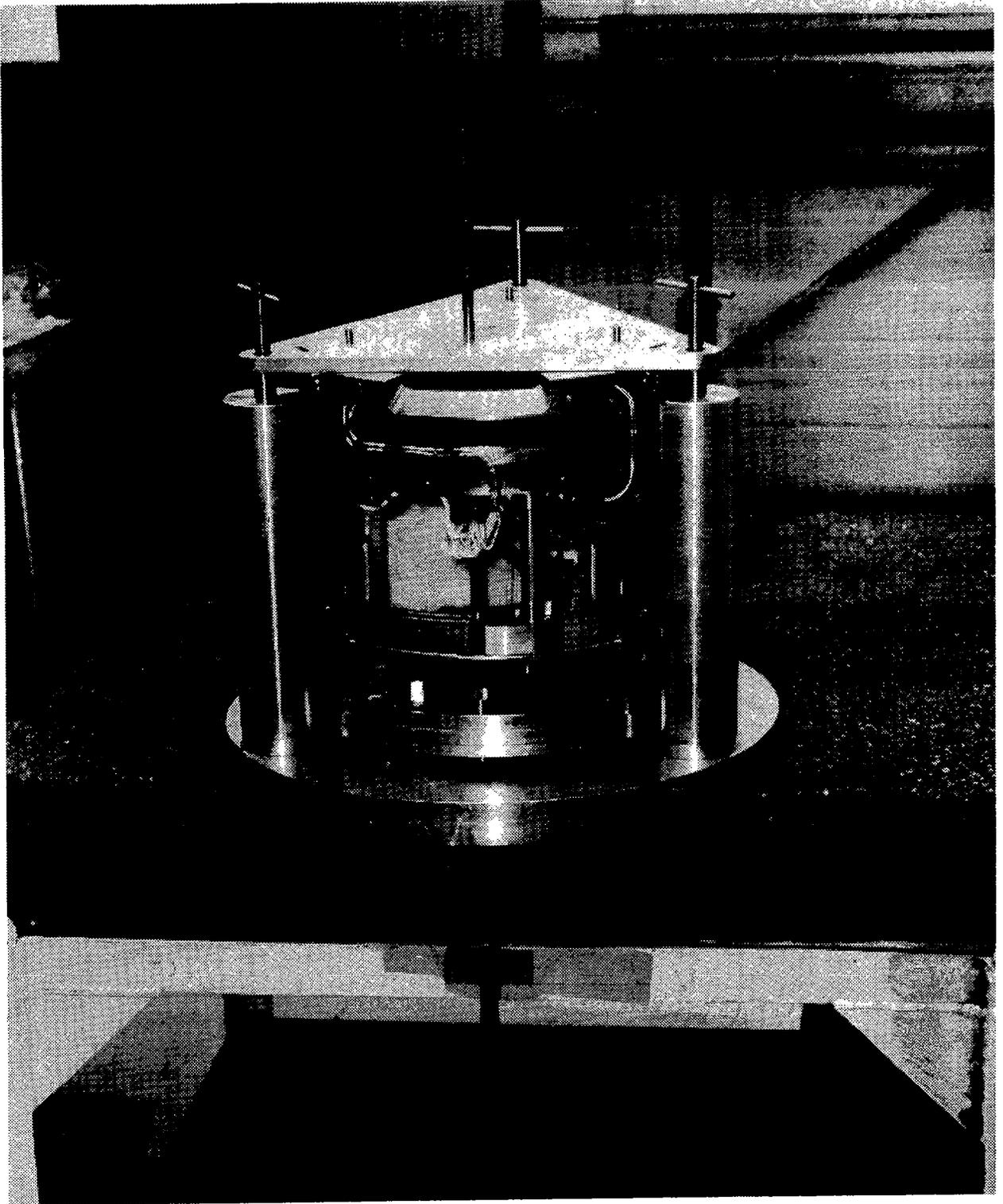


Figure 7. End Effector Alignment Fixture

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