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Development and Testing of the Rack Insertion Device

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Abstract

Installing and removing experiment racks in a Space Station Logistics Module will become a repetitive operation at Kennedy Space Center (KSC) in the near future. A Rack Insertion Device (RID) consisting of an Extendible Boom, End Effector, and Positioning Base is being developed for the task. This paper discusses the key elements of the RID's function and design. Prototype test results for the RID's Extendible Boom and End Effector are presented. Also discussed are future end effectors that will further enhance the RID's Space Station processing capability.

Introduction

Installing experiment racks in the Space Station's Logistics Module will be similar to putting together a ship in a bottle. The Logistics Module, shown in Figure 1, supports sixteen (16) racks in four different quadrants. It has a 2.44-m (96 in) diameter door on one end to simplify rack loading. The module opening reduces to 2 m (84 in) square when racks are installed. For installation, the 816.5-kg (1800 lb) rack must be inserted through the opening, then accurately positioned inside the module for connection. Complicating the operation are the lower, rear, rack-to-module interfaces being hidden from view. The remaining rack-to-module interfaces are two struts connected to the upper, front of the rack. A Logistics Module may be flown up to four times a year to re-supply Space Station, requiring integration of racks each time. Thus, installing and removing racks will become a repetitive process that requires ground support equipment (GSE) that is safe, reliable and time-efficient.

The Rack Insertion Device, shown in Figure 2, is being developed to take a rack out of its support dolly and install it in less than an hour. This will save days in the processing schedule for integrating Logistics Modules based on time-line comparisons with other concepts. The RID concept may also allow processing of multiple rack quadrants without rotating the module, further decreasing processing time. However, decreasing processing time was not the only goal of the RID concept. Limiting risk to flight hardware and personnel was a major priority. One early rack installation concept required technicians to push a rack into position on top of a roller floor, much like loading cargo containers into aircraft. A safe operation would depend on the technician's strength and coordination. KSC Design felt that eliminating man-handling of the rack and reducing GSE-to-GSE transfers of the rack would decrease risk. The RID concept provides positive control of the rack through-out the operation with a push-button control pendant. Also, the RID concept eliminates unnecessary rack transfers.

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Rack Insertion Device Operation

The RID will be operated in the Space Station Processing Facility at Kennedy Space Center. Prior to rack installation or removal, technicians remove the Logistics Module's door and install a GSE personnel floor. An integrated rack, sitting in its support dolly, is staged within the RID's reach. Figure 3 shows a typical rack installation sequence accomplished with the following steps:

<u>Step 1</u>: Rotate and lower the RID's Boom, aligning the End Effector with the rack sitting in its support dolly. Adjust the End Effector to compensate for minor misalignment, then connect it to the rack's GSE handling points.

<u>Step 2</u>: Take the rack's weight off the support dolly and disconnect it from the dolly (the dolly supports the rack in the same manner as the module). The End Effector pivots the rack about its on-orbit pivot location forward 30 degrees.

<u>Step 3</u>: Align the rack with the module's door using the Positioning Base to raise and rotate the Boom.

<u>Step 4</u>: Extend the RID's Boom, aligning the rack with its on-orbit module location.

<u>Step 5</u>: Translate the Positioning Base approximately 0.75 m (2.5 ft) and align the rack with its on-orbit pivot axis. The End Effector can compensate for misalignment and Boom deflection using its adjustment capability.

<u>Step 6</u>: Pivot the rack until it contacts the module support located at the lower, rear portion of the rack. Connect the upper struts and engage the pins, built into the rack, with the lower module support. The rack's weight is transferred from the Boom by adjusting the End Effector. The End Effector design prevents the RID from putting additional loads into the module.

After disconnecting the End Effector from the rack the Boom is retracted and Step 1 is repeated to install the next integrated rack. Rack removal requires the same steps performed in reverse.

The RID, as the concept evolved, has three main components: an Extendible Boom, End Effector, and Positioning Base. The Extendible Boom supports the rack as it is inserted into the module. The Boom not only provides positive control of the rack, it also eliminates the need to design the module for GSE/rack-handling loads. This aspect and the capability for multiple end effectors make the RID very adaptable to flight hardware design changes. The ability to change end effectors will also allow the RID to accomplish many processing tasks other than rack installation. Each end effector will have its own set of requirements and flight hardware interfaces. The End Effector for installing and removing racks in the Logistics Module connects directly to the rack GSE interfaces. It compensates for misalignment and prevents the Boom from accidentally putting loads into the module. The Positioning Base adds flexibility to the RID, providing three degrees of freedom to the Extendible Boom. The Base can raise, rotate and translate the Boom giving the RID the capability to pick a rack out of its dolly without additional transfers. The Base's rotation also allows integration of two Logistics Modules without repositioning the modules or the RID. A discussion of the key design elements for the Extendible Boom, End Effector, and Positioning Base follows.

The Extendible Boom

The RID's Extendible Boom is a critical component in the system. Requirements for the RID called for a boom that extended 8.2 m (27 ft) with a capacity of 1,814 kg (4000 lb). The Boom must handle a torque of 9,040 N•m ($8 \cdot 10^4$ lb•in) and a moment of 22,600 N•m ($2 \cdot 10^5$ lb•in) applied at the Boom's endplate. These requirements provide the Boom with the capacity to install Lab Module racks, should an end effector be designed to do so. The Extendible Boom must support these loads with minimum deflection. If the Boom's deflection is too great, the Positioning Base will constantly have to adjust the Boom's height while extending the rack into the module. Also, the End Effector will require greater adjustment capabilities to compensate for the Boom's deflection. Our goal for the design was to hold the change in Boom deflection to less than 25 mm (1 in) when the rack's weight is transferred from the Boom to the module. The Boom design must maintain minimum safety factors of two against yield and three against ultimate failure.

The Extendible Boom design, shown in Figure 4, includes three telescoping sections and a support structure. Each of the Boom's sections are weldments forming hollow, square tubes (see Figure 5). The material is ASTM A572 steel plate. Top and bottom surfaces of the square tubes were machined for the mounting of hardened bearing ways. The ways are chrome-plated and have a minimum Rockwell hardness of 71C as recommended by the bearing manufacturer. Two upper and two lower linear roller bearings, separated by 1.22 m (48 in), form a couple to support each section. Bearing reactions from the largest tube exceed 125,000 N (28,000 lb). The bearings have a coefficient of friction of less than 0.005 and allow the Boom sections to move quite easily, even when loaded. Originally all of the bearings were to be aligned with shim adjustment only. At the time of manufacture, a spherical mount for the upper bearings was designed to simplify assembly and ensure proper alignment with the hardened way. In addition to the main bearings, rollers react side loading and support the tubes when they are not loaded and are fully retracted. Each of the three Boom sections are actuated independently using a 3.81-cm (1.5 in) diameter ball screw and a stepper motor. The power and control cables are routed through the Boom's sections using separate flexible, metal conduits. Expandable bellows, installed over each section, prevent contamination of the cleanroom environment.

The support structure for the Boom's sections is a welded ASTM A572 steel frame fabricated using standard shapes. To minimize annual inspection requirements, critical welds were eliminated from the design. The support frame has built-in interfaces for the Positioning Base's four jacks to raise and lower the Boom. Two lead-filled counterweights totaling 7879 kg (17370 lb) are mounted on the back of the support structure. The counterweights prevent any upload on the lifting jacks. Linear bearings, mounted vertically on the frame, react side loads to the Positioning Base. The support frame was analyzed using finite-element techniques to ensure its integrity even if one of the four lifting jacks failed.

Rack Installation End Effector

The end effector is the interface between the Extendible Boom and flight hardware. The End Effector, designed to install and remove Logistics Module racks, must compensate for Boom deflection and RID misalignment with the module. Also, the design must prevent over-loading the module with the Boom. Manual operation of the End Effector is preferred, allowing the operator some "feel" as to whether the rack is being adjusted properly. Lastly, the End Effector must provide proper alignment between the rack's rear fittings and the module's interfacing support. This connection is hidden from view if there are racks on either side of the one being installed.

The End Effector provides five degrees of freedom to align the rack. Controls for the Extendible Boom are sensitive enough to align the rack along the module's axis (the x-axis). The End Effector's design concept, shown in Figure 6, uses a simple three-point suspension. Three points describe a plane and no matter where you move one of the points, a plane is still defined. The End Effector supports the rack interface plate at three points, using spherical bearings. The two lower support bearings are independently moved in the "y" and "z" directions. By moving these bearings together or independently, the rack can be adjusted with five degrees of freedom. These two bearings are located in-line with the rack's on-orbit pivot axis allowing the rack to pivot about that axis while supported by the End Effector. The rack's pivot points are not obstructed from the operator's view during installation. If the operator aligns the rack's pivot axis properly in the module, the rack is ensured of being properly aligned with the module's support fittings. Located on the rack's center-line is the third support bearing, connected to a screw jack for pivoting the rack.

The End Effector's two lower support bearings move in the y-direction, actuated by jack screws housed in the bearing's support arm. A ratcheting turnbuckle pivots the support arm providing bearing movement in the z-direction. The turnbuckles and jack screws provide fine adjustment of the support bearings, ±50 mm (2 in). To prevent damaging the module's support fittings with the RID the turnbuckles' design can support only a tension load. If the Boom is mistakenly lowered while the rack is in contact with the module's fittings, the turnbuckles will begin to collapse, alerting the operator of a problem. Only the weights of the rack and interface plate are applied to the module's fittings. This turnbuckle feature also helps the operator sense when the rack's weight transfers to the module.

Positioning Base

The Positioning Base, shown in Figure 7, supports the Extendible Boom and provides three additional degrees of freedom for the RID. The Base design can raise and lower the 15,875 kg (35,000 lb) Extendible Boom within a 2.75 m (9 ft) stroke. This allows the RID to attach to a rack sitting in its support stand on the floor then raise the rack to the module level. The Base can also rotate the Boom 365° to allow processing of two modules without moving or realigning the RID. Finally, the Base translates the Extendible Boom in the y-direction ±1 m (3.5 ft). This motion is necessary to position the rack inside the module. The mechanical systems required to achieve these movements are independent from each other. Each requires a level of structural support. The three systems are stacked with the Jacking System on the top level, followed by the Rotation System and Translation System.

The Jacking System, shown in Figure 8, mounts on a steel support frame 20.3 cm (8 in) deep. A large enclosure surrounds the entire system to preserve the cleanroom environment. Four 27,000 kg (30 ton) acme screw jacks raise and lower the Extendible Boom. The off-the-shelf jacks have a 7-cm (2.75 in) diameter acme screw. There is a 4 to 1 safety factor against buckling for the highest loaded screw. The jacks have a 9:1 gear reduction built in and a 10:1 gear reducer connects to each jack to further reduce the motor torque required. Rather than a single drive motor, two servo-motors drive the four jacks, one between each forward and rear jack. Two motors were used for several reasons. Having two motors decreases the length of the transmission shafting required. This lowers the inertia of the system and decreases the potential for shaft wind-up. Also, having two motors with fail-safe brakes in the system eliminates a single-failure point. Should some portion of the Jacking System fail, such as a shaft or coupling, three jacks are still connected to a brake. Finally, the size and cost of a single servo-motor, large enough to drive all four jacks, was much greater than the two motors used.

The Base's Rotation System design, shown in Figure 9, can rotate the Extendible Boom and the Base's Jacking System 365°. To decrease inertia, the two smaller Boom sections must be retracted prior to rotating. However, that still translates into an inertia of 13,333 kg•m^2 (118,000 lb•ft•s^2). A large diameter roller bearing with an integral gear was our first consideration for the Rotation System. It became impractical because of the size and cost of the bearing required. The rotation bearing had to be mounted directly underneath the jacking screws to minimize the depth and deflection of the Jacking System's support frame. This required a bearing 4.25 m (14 ft) in diameter. The few manufacturers that were able to make such a bearing gave quotes of 70 to 100-thousand-dollars with a year's lead time. A much cheaper and equally capable system was designed using multiple components. Sixteen 7.6-cm (3 in) diameter yoke-style rollers mount directly below the jacking screws on the Jacking System's support frame along a 4.25-m (14 ft) diameter. The sealed rollers operate on hardened-steel ways mounted to the Rotation System's structural frame. Also mounted to the Rotations System's support is a 2.44-m (96 in) diameter spur gear with external teeth. The mating pinion mounts to the Jacking System's support frame. It provides a 14:1 torque reduction and rotates the frame when driven. Even with the large gear, the pinion starting torque required calculates to be 1,119 N•m (9,900 in•lb). A servo-motor drives the pinion through a 200:1 gear reduction. Cam-followers, rolling on the inside diameter of the spur gear, take care of side load. The power and control cables that route down to the next level are the only limitation to infinite rotation of the Boom.

The Base's Translation System, shown in Figure 10, moves the Extendible Boom as well as the Base's Jacking and Rotation Systems totaling about 36,300 kg (80,000 lb). The system comprises of linear bearings used with a rail and a ball screw actuator. Four linear bearings are equally spaced on two parallel rails. The linear bearings mount to the bottom of the Rotation System's structural frame. The ball screw provides controlled movement and mounts to the Translation System's structural support. The ball nut bolts to the Rotation System support. The linear bearings' coefficient of friction being low, the ball screw's calculated starting torque is also relatively small, 11.5 N•m (100 in•lb). However, to reduce the system inertia a 10:1 planetary drive is used in conjunction with the drive motor. Also mounted to the Translation System's support are hand-operated lifting jacks. These jacks can lift the RID in order to place air bearings underneath. Air bearings are the means used to move heavy stands and equipment in the Space Station Processing Facility at KSC.

The Positioning Base's structural components, like the Extendible Boom's, are designed with safety factors of two against yield and three against ultimate failure. The Base is made almost entirely from standard structural steel shapes with the exception of the Rotation System's support frame. This frame will be fabricated from steel plate. Again, a finite-element program was used to solve for the loads in each structural member. Various different load cases, based on the many possible RID positions, were required to find the maximum loading in each member. Like the Extendible Boom, the Positioning Base was designed without any critical welds.

Controls

Computer-programmed stepper and servo motors drive all of the RID's powered systems. The use of this type of motor gives precise control of the mechanical elements and allows changing the travel speed and acceleration by modifying the drive program. It also allows future consideration for automating all or portions of the RID operation. However, the motors required greater care to match the mechanical system's inertia with the drive motor's rotor inertia. In fact, all of the motors were selected on this basis rather than torque or speed limitations. With the current design the operator controls the motors with a push-button pendant (see Figure 11). The pendant is located at the end of the Extendible Boom along with a separate emergency-stop pendant. A master control station, located on the Positioning Base, can also be used to control the RID. Redundant limit switches for all of the powered system's end-stops prevent over travel.

Prototype Testing

Fabrication of the Extendible Boom and End Effector was completed in June, 1994. Both items were proof-loaded at 125% of their maximum design load. The change in Boom deflection that occurs when the rack is removed from the End Effector, met our expectations. The net deflection was only 1.27 cm (0.50 in) which is well within the adjustment capability of the End Effector. The calculated deflections of the boom for various cases are shown in Table 1. The deflection at the rack pivot point is given which includes the torsional deflection of the Boom.

Table 1. Extendible Boom Deflections

Case	Weight	Torque Arm	Moment Arm	Def. @ Rack (Calc.)
125% Capacity	22.2 kN (5000 lb)	127 cm (50 in)	117 cm (46 in)	4.44 cm (1.75 in)
100% Capacity	17.8 kN (4000 lb)	127 cm (50 in)	117 cm (46 in)	3.75 cm (1.45 in)
End Effector w/Rack	13.3 kN (3000 lb)	58 cm (23 in)	88 cm (35 in)	2.13 cm (0.84 in)
End Effector w/o Rack	5.3 kN (1200 lb)	58 cm (23 in)	88 cm (35 in)	1.14 cm (0.45 in)

To prove that the RID concept could successfully install and remove a rack, a Logistics Module simulator, shown in Figure 12, was built. The simulator has very high-fidelity with the Logistics Module's rack mounting brackets and interior clearances (Figure 13). The dummy rack used for the test was modified to support 816 kg (1800 lb) and to mimic the actual rack's module interfaces. Without the Positioning Base, a support stand was fabricated to hold the Extendible Boom at the module opening's height. No vertical adjustment was provided. The support stand was equipped with rollers to provide horizontal translation like the Positioning Base. The dummy rack was installed on the End Effector using the facility crane. The first attempt to install the rack in the module simulator went very well with the installation taking just over thirty minutes. No alignment guides or sensors were required. Technicians are able to visually align the rack being installed using the adjacent rack's pivot points as a guide. The dummy rack has since been installed and removed over twenty times in the simulator without inciden (Figure 14).

To convert the Extendible Boom and End Effector into certified GSE, the designs must be put through a Critical Design Review. Prior to that review some changes will be made to the designs based on lessons learned during the prototype testing. The largest impact will be to modify the linear bearing supports for the Extendible Boom. The current design requires each tube section to be removed sequentially to access the bearings. Modifications will be made to simplify bearing replacement in case of a failure. Also, bearing ways will be added for the side rollers. It was first thought that the loads in these rollers would be negligible. As it turned out, the linear bearings have a tendency to find a groove that forces the tubes into the rollers, creating a much higher load. The rollers, bearing against the primered steel, cause flaking that could be a contamination issue. Modifications planned for the End Effector include providing a captured-screw connection for the rack and incorporating the "y" axis screw jacks into the support for greater module clearance. We also plan to add instrumentation to End Effector to measure the weight and cg of the rack. By incorporating weight and cg measurement into the End Effector, a number of operations and rack transfers are eliminated, further reducing processing time and decreasing risk to flight hardware. Prototype testing of the weight and cg components are on going.

Other End Effectors

Although the RID was designed to install racks, there are many processing tasks that the RID is capable of performing. Changing end effectors allows the RID to interact with different pieces of flight hardware. End effectors are being developed or considered to perform the following operations:

- Installation and removal of Lab Module and Node racks
- Installation and removal of the Logistic Module's large diameter door
- Opening and closing of the 1.27 m (50 in) hatch
- Late and early personnel access to the module
- Installation and removal of rack drawers/large components/replaceable units

Late and early personnel access to the module may be impossible without the RID. Alternative methods for the other above operations, not using the RID, require extensive amounts of GSE. Using the RID to perform the above operations will reduce the flight hardware processing time and GSE requirements.

Conclusion and Summary

The Rack Insertion Device is scheduled to be activated in March, 1996. The Extendible Boom and End Effector prototypes have been thoroughly tested and are currently being converted to GSE. Their testing has proved that an 8.2-m (27 ft) long extendible boom can accurately and dependably position equipment the weight of a small car with the push of a button. Delivery of the Positioning Base is expected in August, 1995. Once the RID is complete, it will be one of the more expensive and complicated GSE systems at Kennedy Space Center. However, no other concept would have made the Logistics Module's rack installation operation as efficient or safe as the RID can. With the development of additional end effectors, the RID will become an integral part of Space Station processing.

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Jim Porterfield . . .	Extendible Boom and Positioning Base structure design
Scott Strickland .	End Effector design and Positioning Base mechanical design
Harry Garton	Extendible Boom mechanical design
Tien Chi Ma	Extendible Boom and Positioning Base finite element analysis
Jon Gleman	Extendible Boom and Positioning Base powered systems
Steve Mullen	Extendible Boom and Positioning Base cable systems and controls
Don Taylor	Positioning Base powered systems

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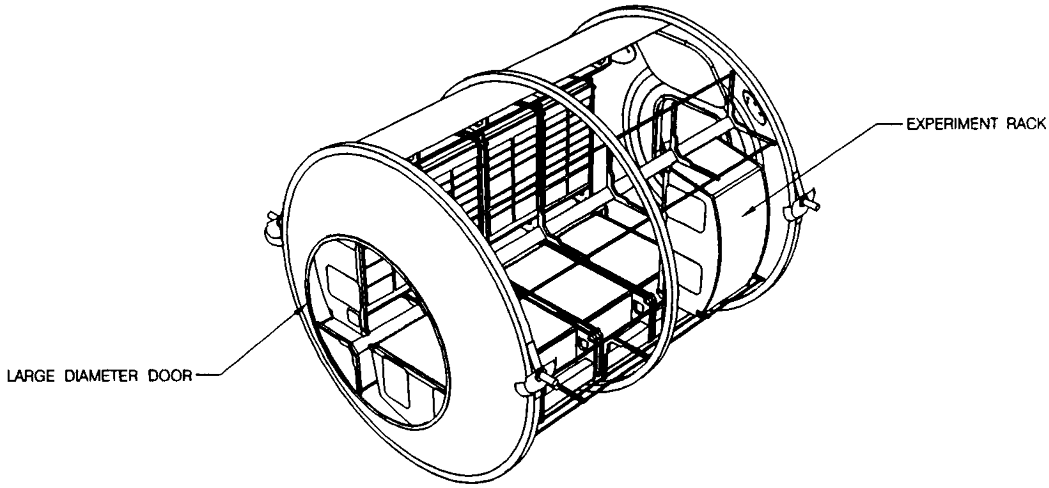

Figure 1: The Logistics Module

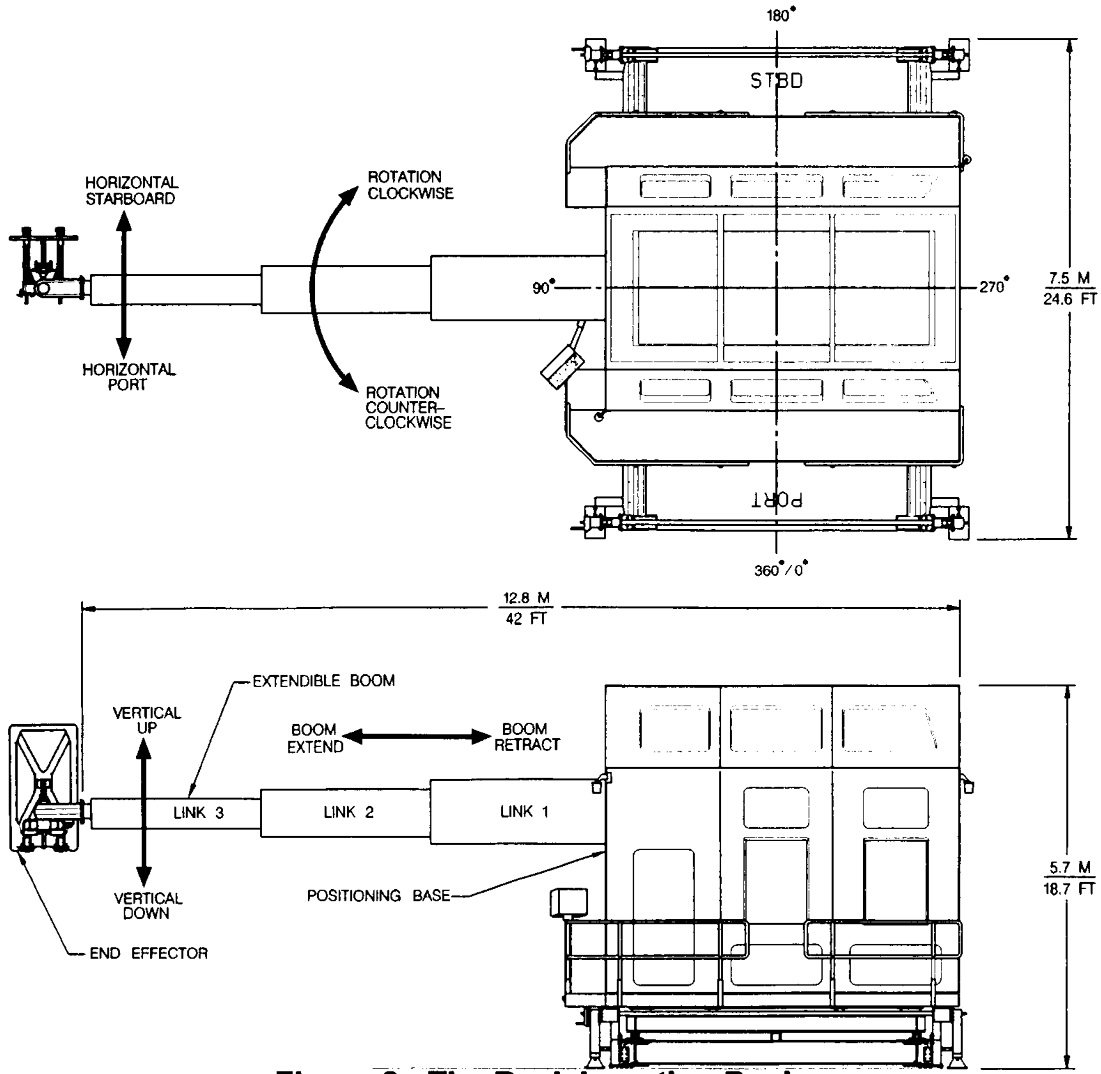

Figure 2: The Rack Insertion Device

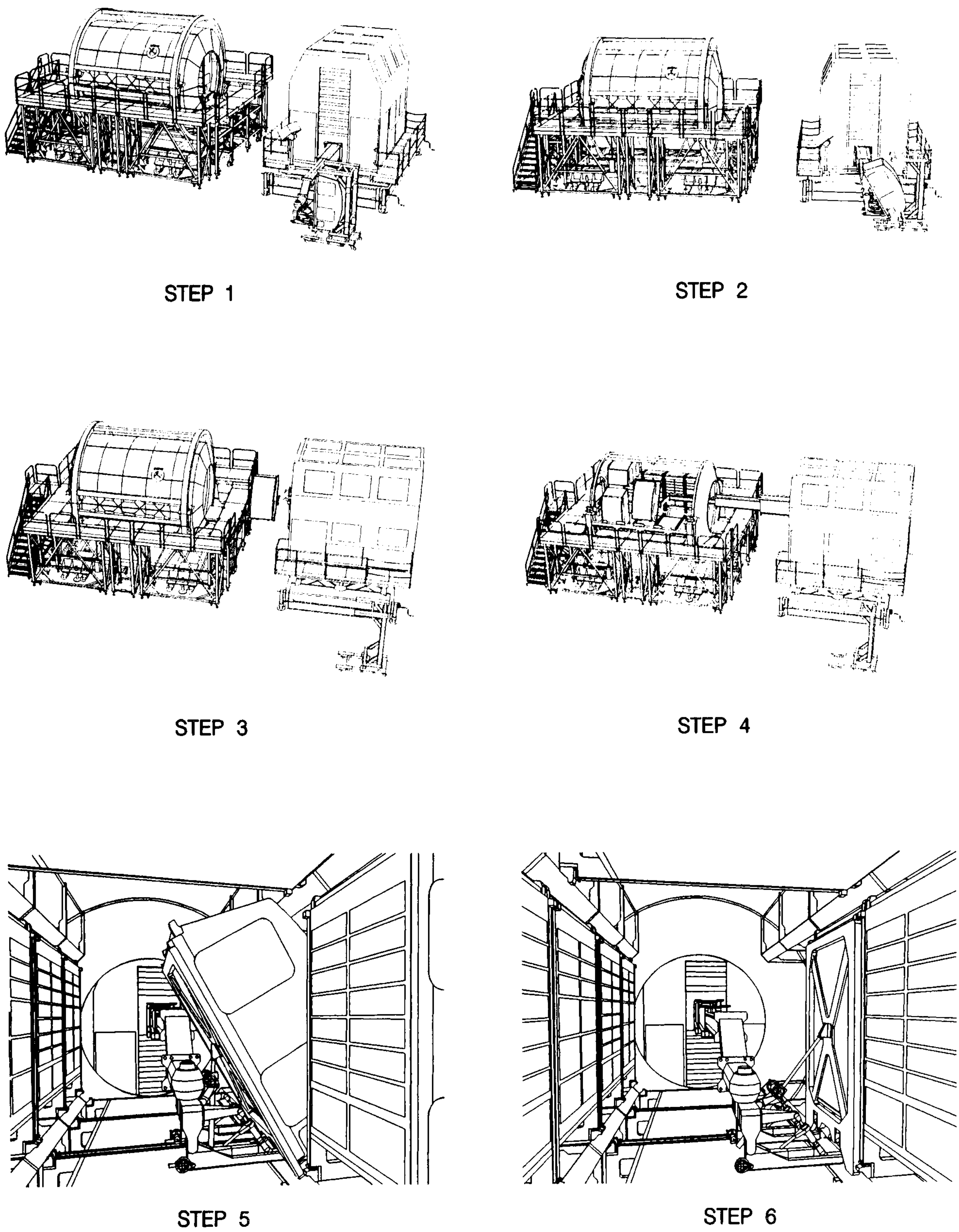

Figure 3: RID Operational Steps

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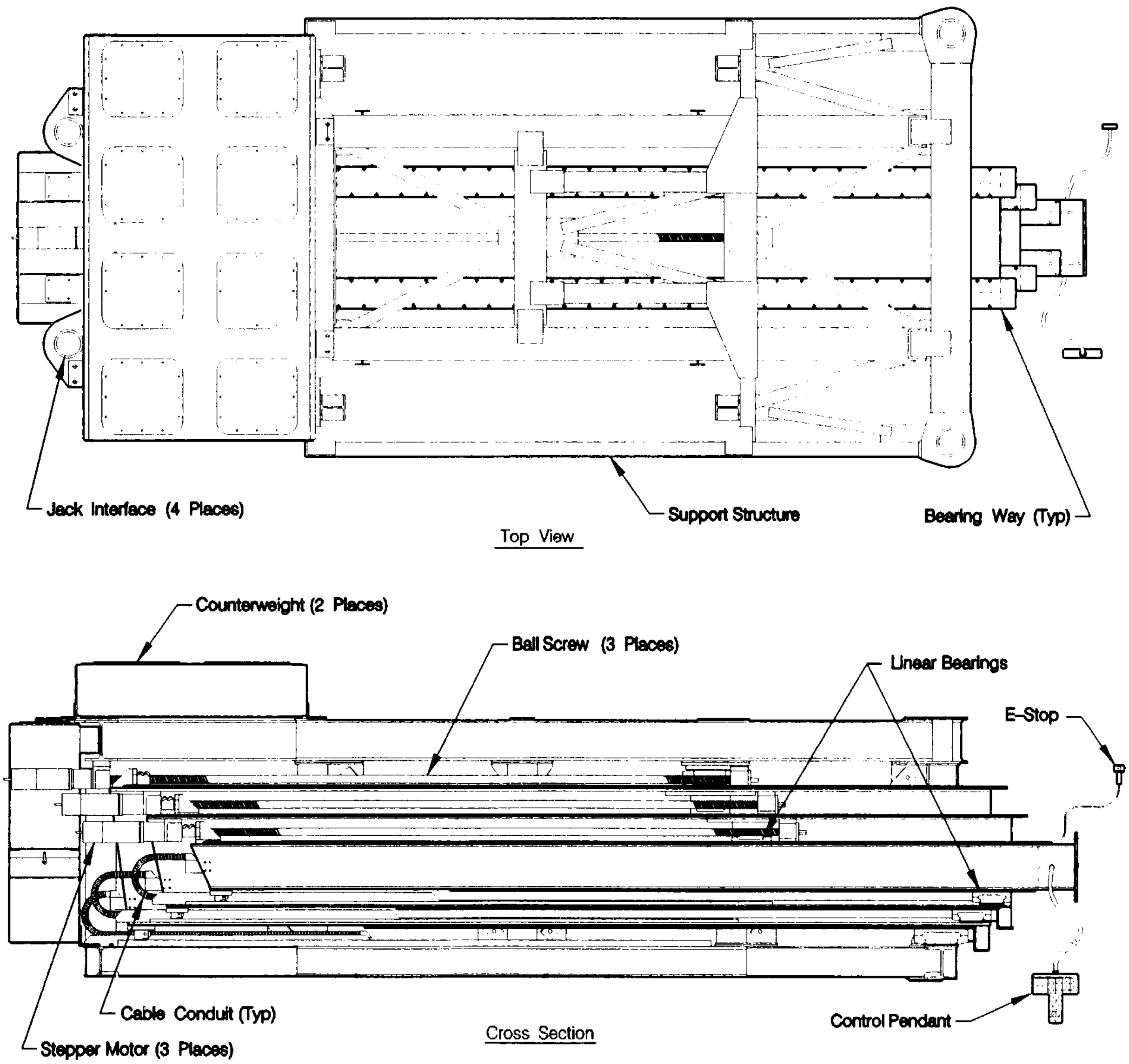

Figure 4: The Extendible Boom

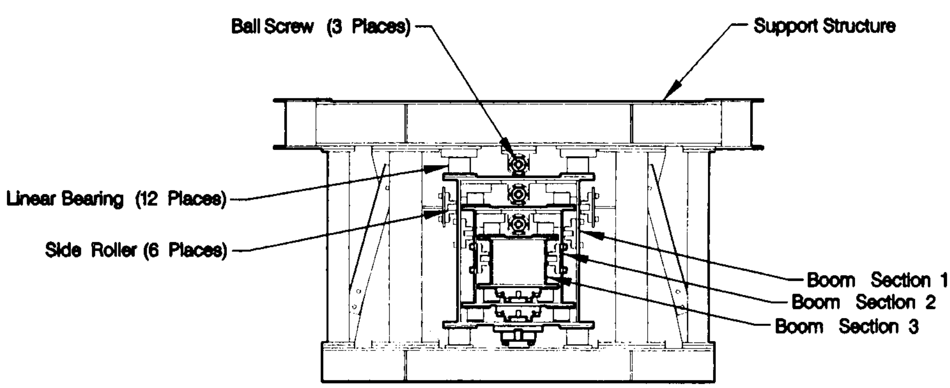

Figure 5: Tube Arrangement

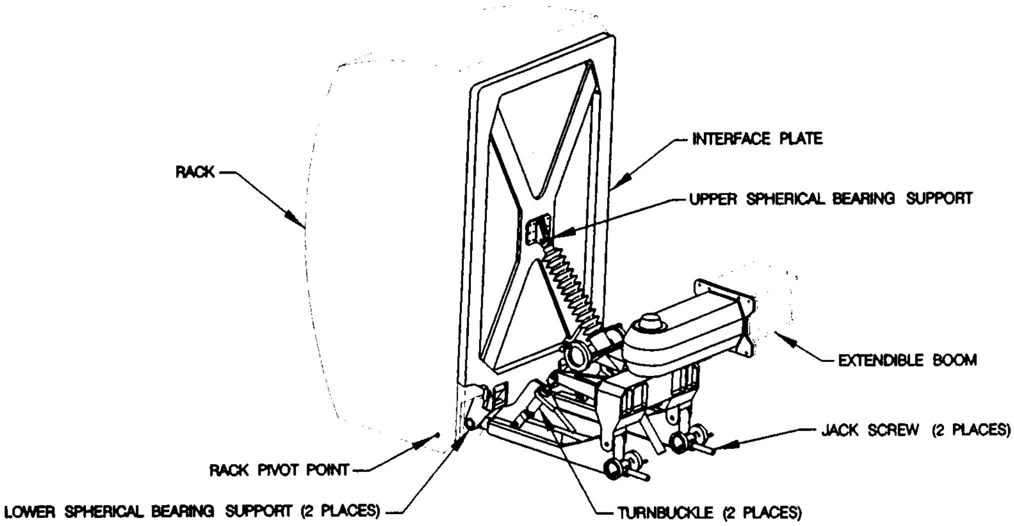

Figure 6: End Effector (Installed Position)

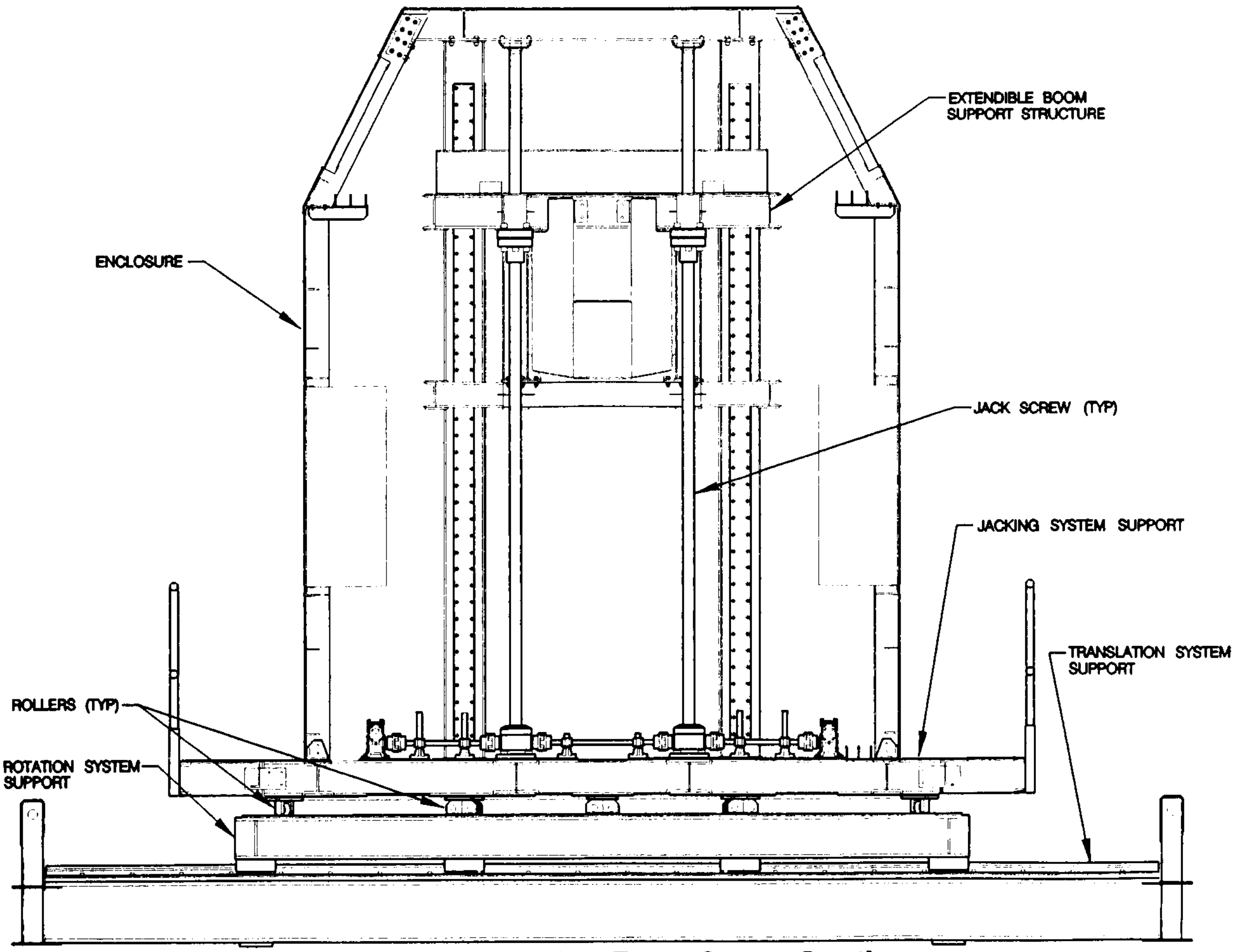

Figure 7: Positioning Base Cross-Section

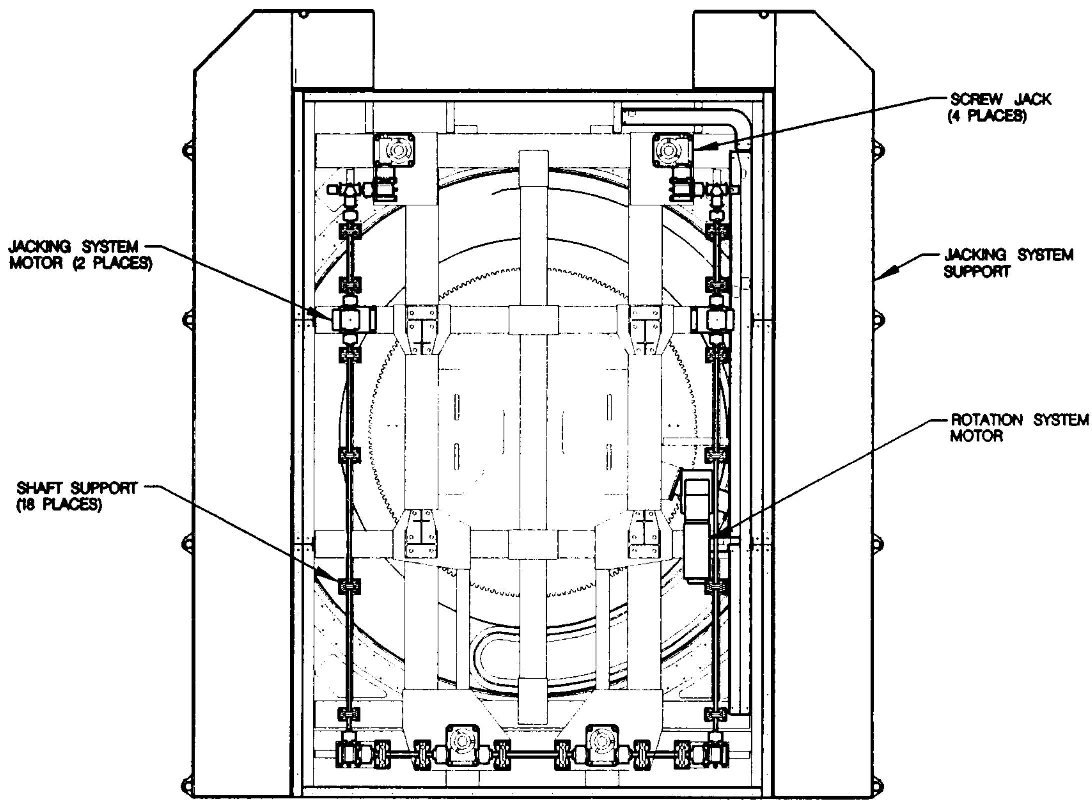

Figure 8: Positioning Base Jacking System

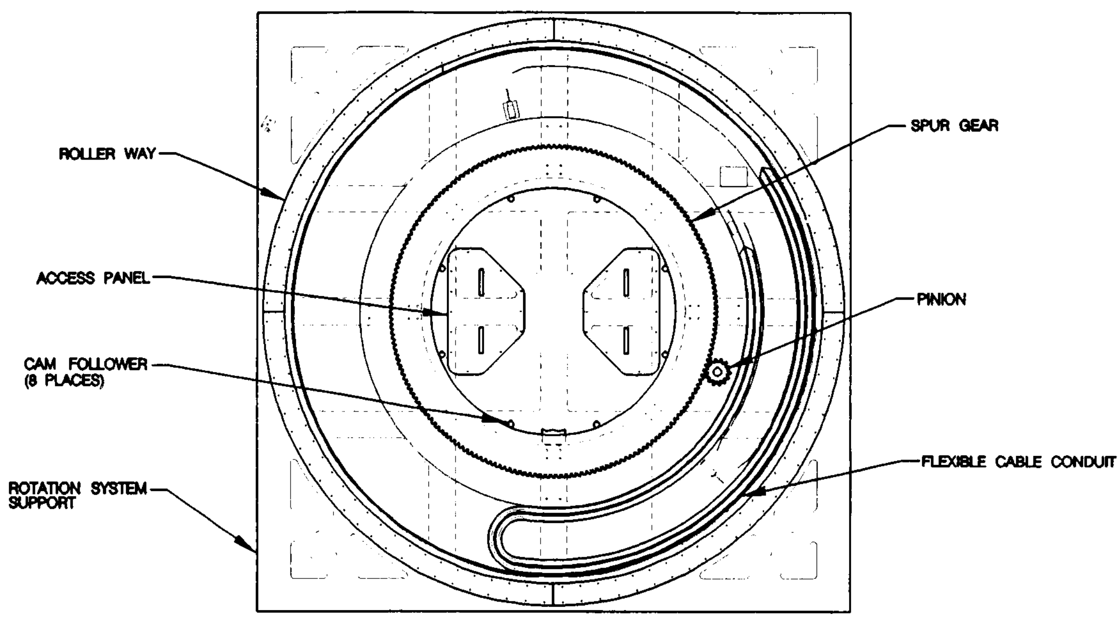

Figure 9: Positioning Base Rotation System

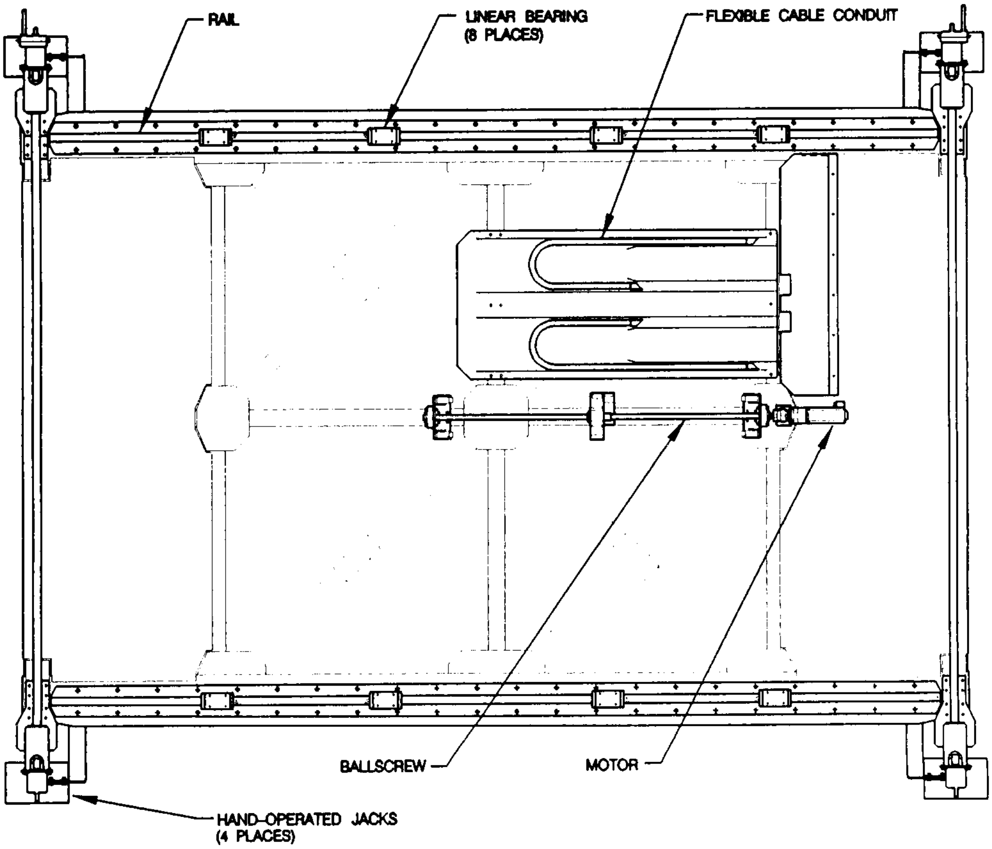

Figure 10: Positioning Base Translation System

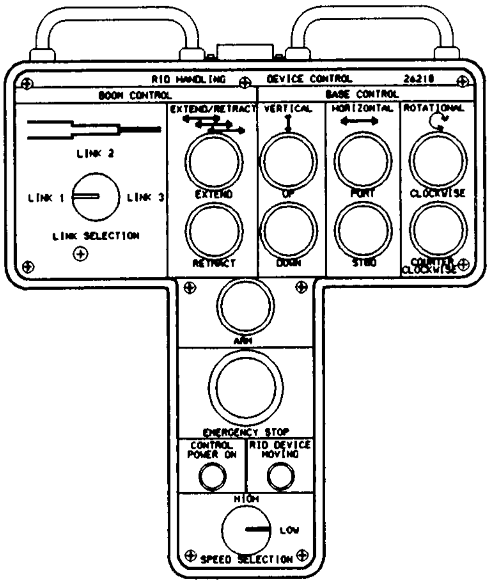

Figure 11: RID Control Pendant

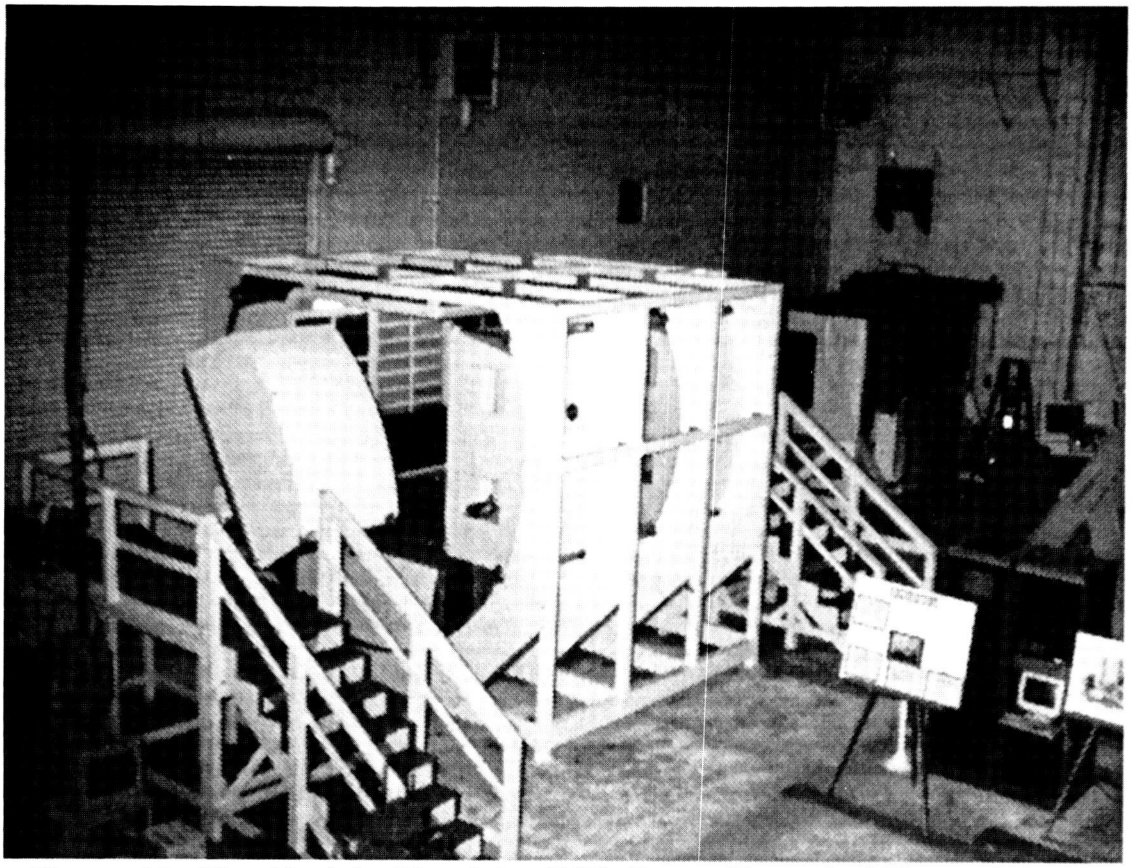

Figure 12: The Module Simulator With Boom Extended Through It

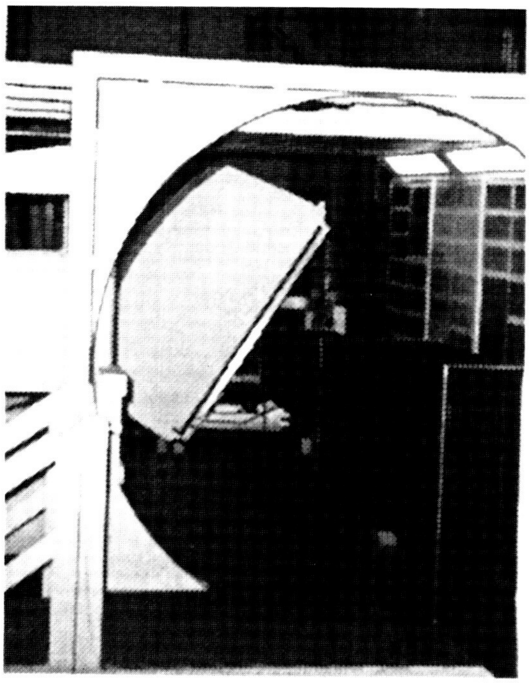

Figure 13: Rack Being Inserted by the Boom

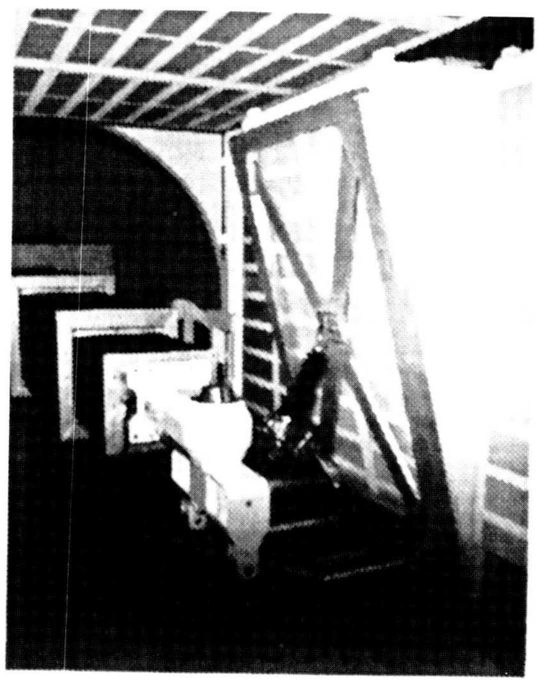

Figure14: Rack Being Installed