Retrofitting a Fine-Pointing System to Satellite Optics

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Abstract

This paper describes a system added to an existing satellite-borne telescope design for the purpose of compensating the boresight errors that had been observed in earlier flights of similar instruments. Those errors had been found to be caused by thermal distortion of the spaceframe. This retrofit design was subjected to severe volume restrictions because it was fitted into an already tightly-packaged instrument envelope. It was found practical to improve the basic design by converting a redundant structure into a statically-determinate one. It was also possible to use portions of the mechanical actuation system to facilitate the position encoding needed for computer interfacing.

Introduction

Pointing information for this optical system is obtained from a star sensor that is located at some distance from the instrument itself. Thermal distortion occurs in the intervening structure, leading to boresight errors. These errors have been investigated by ground reference and found to be a reproducible function of the diurnal and annual cycles. It is possible to characterize this error with enough precision to permit uploading a protocol that controls a fine positioning system and removes the error at its source. In the case described here, it was necessary to input corrections having a resolution on the order of one arcsecond and a net excursion of approximately one half degree of arc. During an initial evaluation of the design problem, it was thought that a second electronics package would be required in addition to a substantial increase in the volume of the existing envelope. This would have caused a major dislocation because of the limited "real estate" available on the satellite platform, and because of the need to negotiate with numerous other experimenters whenever a change in geometry took place. To avoid these complications, it was taken as a design objective that any additional systems be entirely contained within the existing envelope. It was found that this was, in fact, possible.

The Basic Structure

The skeleton of the existing system is shown in Figure 1. It is a beryllium structure comprising a frame within a frame and having a square "footprint" on the mounting platform. The structure had been designed as two discrete entities in order to allow manual boresight adjustment of the telescope during its initial assembly. This feature provided an existing interface at which to input relative motion between the optical elements and the parts of the structure that were "grounded" to the spaceframe. The square cross section is clearly not optimum for a precision pointing system because it

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is redundant. The geometry had been dictated by space constraints, being the only available volume on the satellite platform at the time of initial design. The square cross section did, however, have one intrinsic advantage. It was found to provide an already existing pair of orthogonal axes which could be used for X-Y pointing of a telescope. The structure also had what is, in effect, a universal joint at each of the four supporting corners. These ("monoballs") had been incorporated in the original design to minimize the distortion of the structure that would be caused by joint moments.

Pointing Modification

Two-axis pointing was accomplished by choosing one of the four support points as the only fixed "ground," locking the diagonally-opposed support point during launch and releasing it in flight, and placing actuators on the remaining two corners to move them normal to the plane. This is indicated conceptually by the sketch in the lower right-hand corner of Figure 1. It can be seen that if the upper right corner of the square is held at a given elevation and the lower right corner raised or lowered, rotation will occur about the horizontal axis. A similar rotation can be obtained about the vertical axis by motion at the upper left corner. The lower left corner is unsupported.

A study of the interior of the existing design revealed that the only sizable empty volumes were in the spaces immediately above the four monoball universal joints. This suggested that, if these spaces were to be used, each actuator would have to be extremely compact or each would have to be divided into two separate functional units. The latter course proved to be practical and, in fact, it was later found to be convenient. The approach that was ultimately chosen is shown schematically in Figure 2 where much of the detail is devoted to the position pickoff arrangement. This proved to be more challenging than the motion itself. Each actuator consists of two parts that are mounted at opposite ends of a lever. Each lever spans an edge of the square. Motion is accomplished by a stepper motor, which drives a lead screw through a gear train. This moves the long arm of the lever via of a pair of ball bearing nuts that have been spring loaded to eliminate backlash in the overall assembly. The shorter arm of the lever is shown in Figure 2 as being between a pair of bearings, the left one being the fulcrum and the right connected to "ground." This drawing is conceptual. In fact, the short arm of the lever is so small that it is really embodied by an eccentric mounted in the bore of a large fulcrum bearing. This can be seen by comparing Figure 2 to Figure 3. The latter shows the actual hardware as it was installed in the instrument. Specifications of this retrofitted system are as follows:

Angle increment per step:	1.1 arcsec
Total angular excursion:	0.43 degree
Number of steps (Full travel):	1408
Movement per step (At end of short lever):	914 nm (36 μin)
Net Travel (At end of short lever):	1.32 mm (0.052 in)
Total Lead Screw Revolutions (Full travel):	22
Total Motor Revolutions:	176

Since the system operates in a closed loop, determining the true location of the positioner to feed back to the onboard computer is a vital part of the operation. Not only is accurate position data needed, these data must come from absolute position encoders that will not be rendered useless in the event of a computer upset. Position encoding was incorporated by converting the leadscrew arrangement into an analogy of a mechanical micrometer. In both, a small deflection is measured by determining the angular position of a screw in its rotational cycle and interpreting this data in the light of knowledge regarding the specific pitch of the screw in which the angle data are taken. This concept was put into practice using a pair of encoders, which involved the Gray code [1] for digital output. One encoder was placed on the long lever arm and served to determine where the ball nut was in relation to the leadscrew. This gave a coarse indication of position. Fine position was indicated by an angular encoder attached to the lead screw. A "hardware" constraint influenced the design of the encoders. Only specific flight-qualified semiconductor components could be used in the light emitting diode/phototransistor pair that is used to provide digital position data. This led to a fairly bulky assembly. Pickoffs took the form of the sector encoder and rotary encoder set shown in Figure 2. The sector encoder may also be seen in Figure 3; the rotary encoder is not visible, being enclosed by the leadscrew housing in this figure. The stepper motor which turns the leadscrew advances 45 degrees per step. This, driving through a gear ratio of 8:1, gives 64 steps per revolution of the screw. The arrangement was chosen to make binary arithmetic easier. The pitch of the leadscrew is 1.27 mm (0.050 in) and the resolution of the coarse encoder is on the order of 80% of this distance.

A complication in using a pair of digital encoders in this fashion is the mechanical backlash and other accumulations of tolerances guarantee that when the coarse encoder changes state, it cannot be guaranteed do so every time at exactly the same transition indicated by the fine encoder. The problem of seaming together the outputs of two encoders in the presence of mechanical hysteresis has been discussed in an earlier publication [2]. Briefly, we have shown that as long as the hysteresis can be kept within calculable limits, unambiguous data can be generated and evaluated with the help of an onboard computer.

The Launch Lock

A mechanism that is fundamental to the operation of the system, but which is functioned only once during the flight, is the launch lock that constrains one corner of the square. The design of this component, too, had to satisfy a number of constraints -- not the least of which being that it had to fit into a volume only a little larger than the featureless column that supported the original assembly. In addition, it was required that it be able to lock the structure wherever it happened to be within its range of adjustment during manual boresighting, and to do so without perturbing that adjustment. The first constraint was satisfied by creating a linear assembly using a long gearhead motor that had a relatively small diameter. The latter requirement was met by creating a collet assembly, much like a lathe collet, which would grasp a cylinder attached to one corner of the moveable structure. The arrangement is shown in Figure 4. The bottommost component in the drive train is a DC motor with a gearhead. This, and the rest of the assembly, is housed in a beryllium column that matches the thermal expansion coefficient of the balance of the structure. The motor drives a screw that incorporates a ball thrust bearing. The screw and bearing are combined into a single component so that the only external loading is the torque which turns it. This minimizes the tendency of the assembly to be deflected axially during operation and allows the collet to grasp a pin without perturbing its axial adjustment. Rotation of the screw causes steel balls to move in inclined races and opens or closes the jaws of the collet. The pin, which is grasped by the collet and which serves to fix one corner of the square during launch, runs in a linear ball bearing. When the collet is opened, this pin is completely free to move in an axial direction. Position of the nut -- and hence the state of the collet -- is monitored by micro switches that sense both limits of its travel. In order to make the collet clamping force adjustable from outside the assembly, this radial force is generated by a screw-adjustable collar surrounding the housing. The collet and ball assembly are run at a very high stress level. For this reason, the collet is made of 18 Ni maraging steel hardened to RC 57. The cylindrical pin which it grasps is 440C CRES hardened to RC 55. Since maraging steel is not resistant to corrosion, the collet assembly is gold plated.

Lubrication

Throughout, an effort was made to use sputtered molybdenum disulfide as a lubricant wherever possible, particularly on the ball screw and main bearings. This was done because of the proximity of the entire mechanism to optical components that would be degraded by off-gassed lubricants. In the case of the DC motor, use of a solid lubricant was not possible. The motor was therefore packaged in such a way as to provide only a very labyrinthine path to the outside and was lubricated with Braycote 600.

References

1. Gray, H. J., et al. "An Analog-to-Digital Converter for Serial Computing Machines." *Proceedings IRE*, 41, no. 10, 1462-1465.
2. Woods, R. O. "An Autonomous, Closed-loop Pointing System for use with Satellite Optics." *SPIE Proceedings*, 817, no. 08

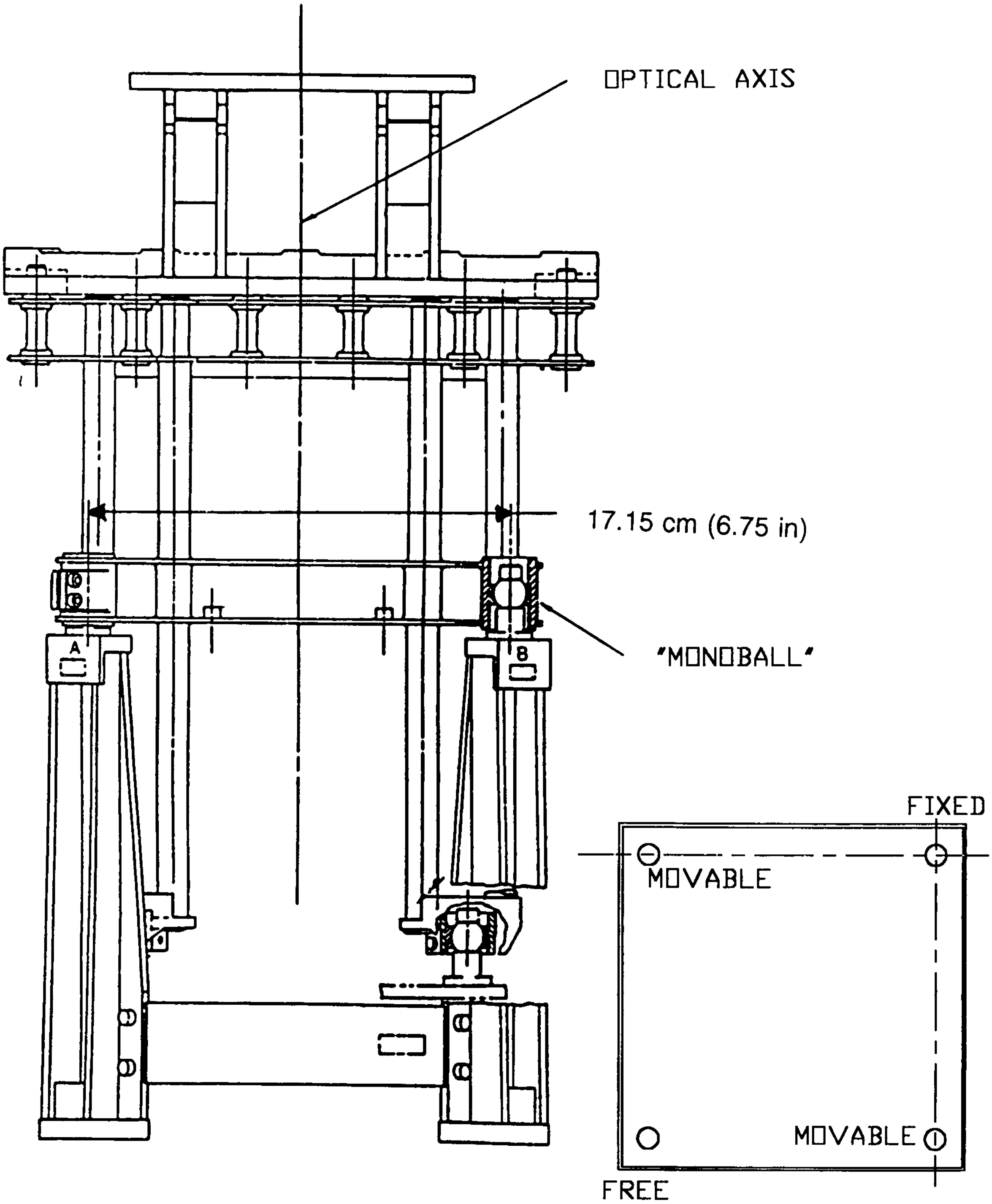

Figure 1. Original Frame

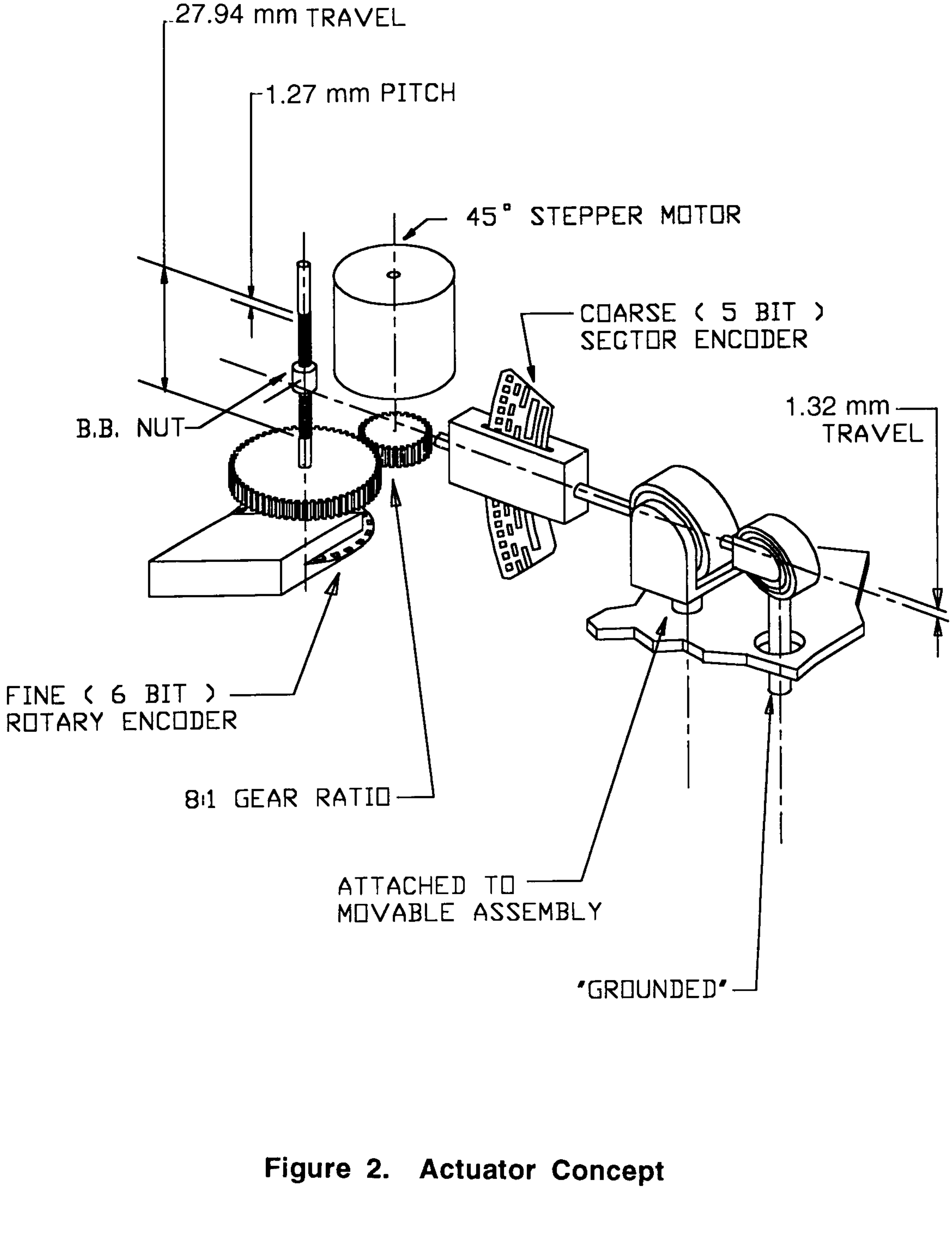

Figure 2. Actuator Concept

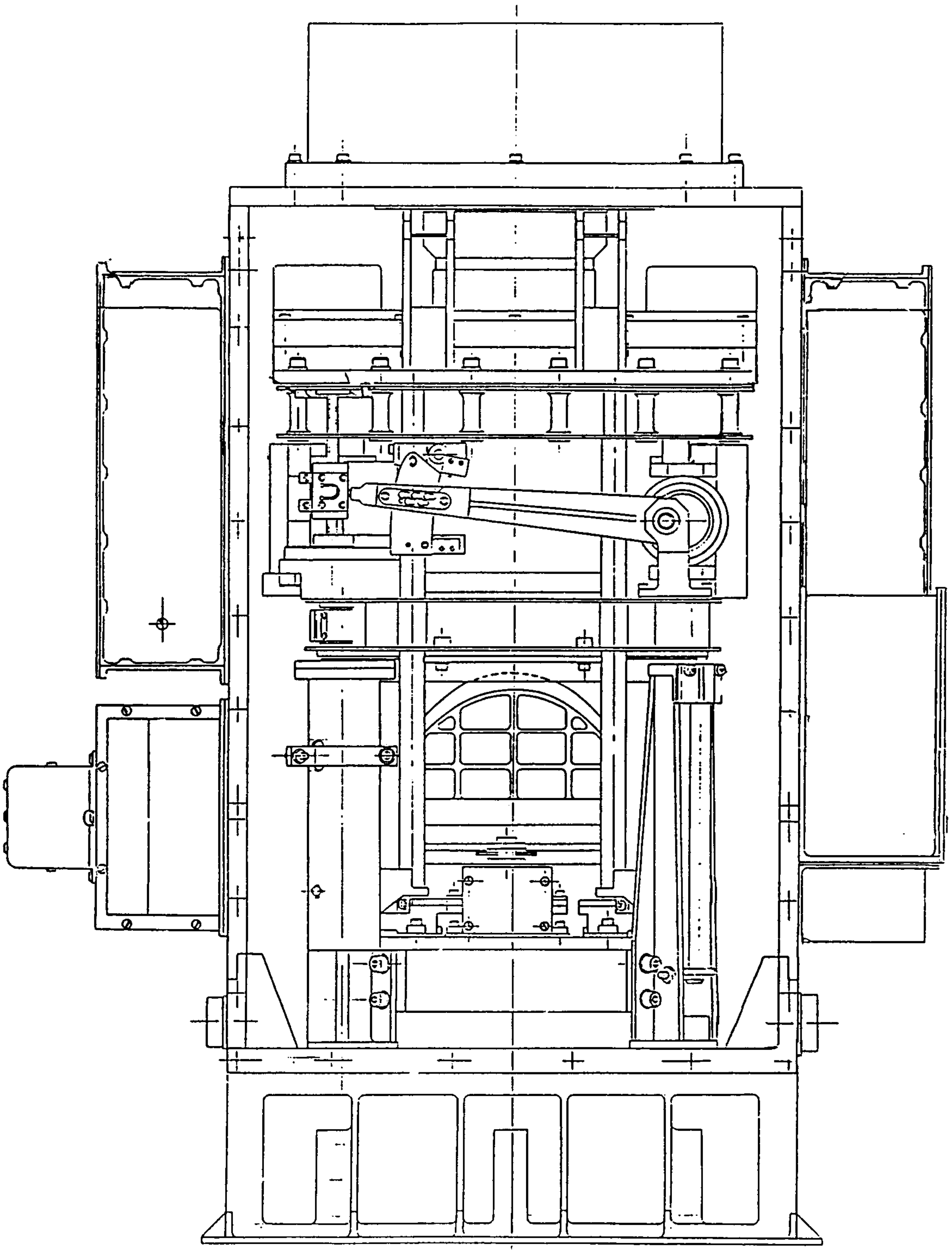

Figure 3. Actuator As Installed

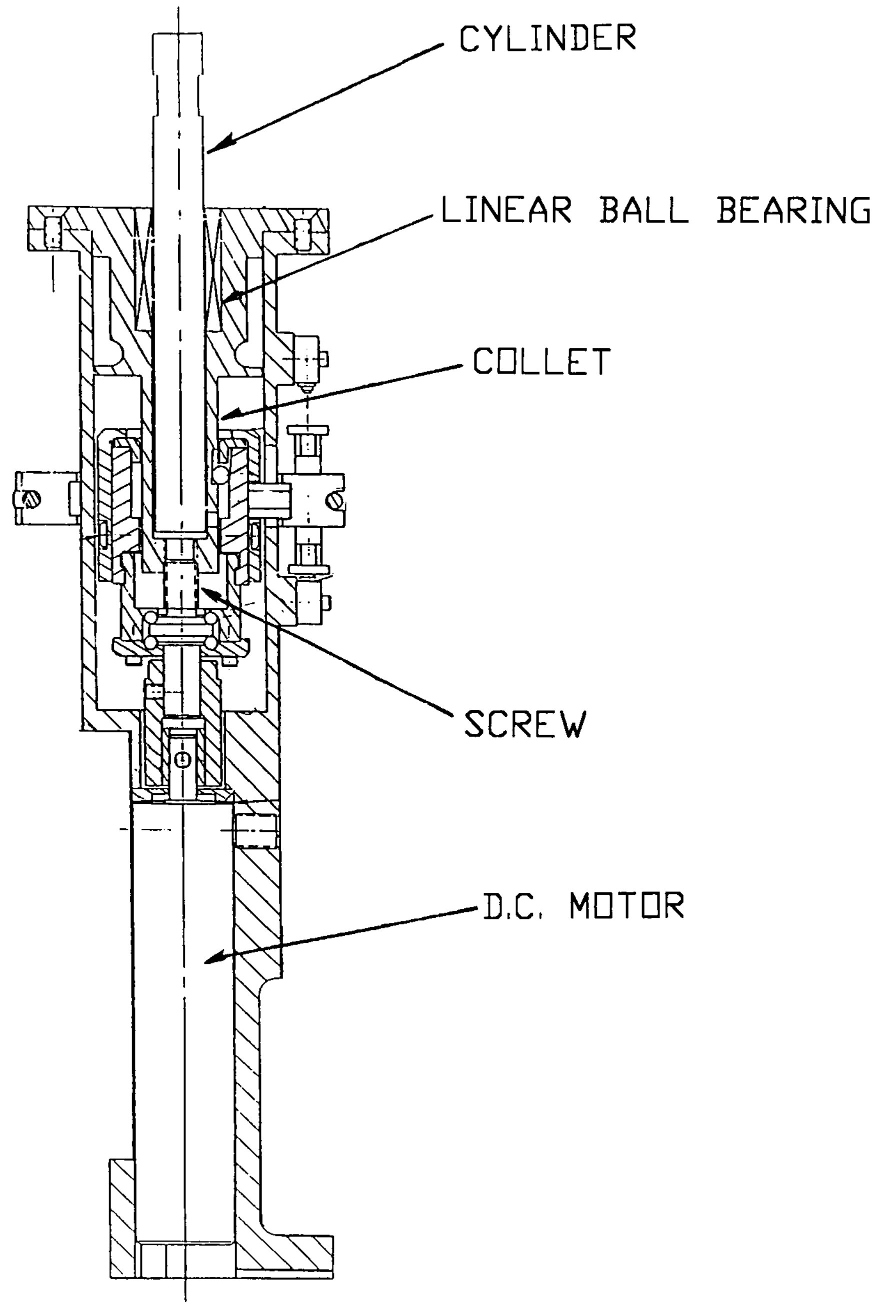

Figure 4. Launch Lock