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DISPLACEMENT SENSORS AND ACTUATORS NEEDED TO CONTROL A SEGMENTED PRIMARY MIRROR

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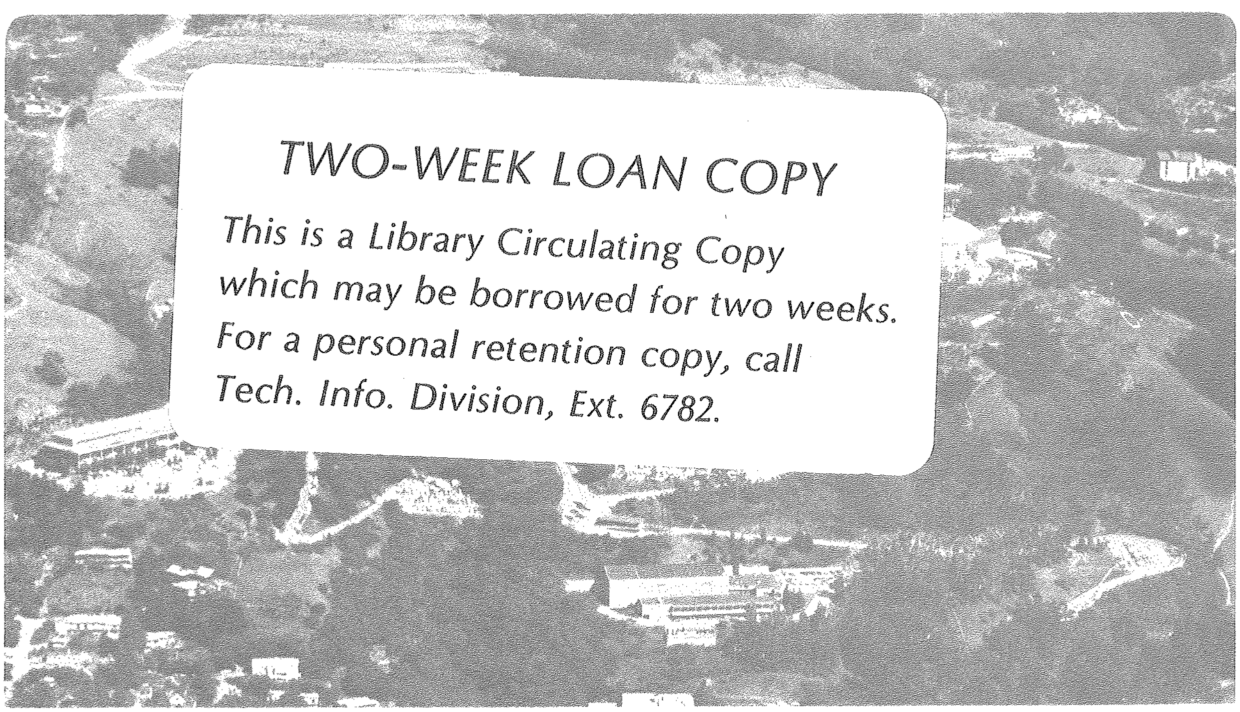

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ABSTRACT

A segmented primary mirror control system was developed for use in the proposed University of California ten meter optical telescope. The general design goals for a displacement sensor and position actuator are listed. A sensor and actuator which were built are described with some test results. A brief senario is given of how these two units would be incorporated into a primary mirror.

INTRODUCTION

A segmented primary mirror control system has been developed for the proposed University of California Ten Meter Telescope (TMT). Three main functional elements are required for figure control of a segmented mirror. They are sensors, to measure the location of each segment's surface in relation to its neighbor's, a control algorithm, to convert the sensor readings into correction signals, and position actuators to move the segments. The figure control algorithm has been discussed in a previous paper.(1)

I will discuss the U.C. segmented mirror design briefly and how it effects the design of the sensors and actuators, give the general design goals for the sensors and actuators, then describe a sensor and actuator which have been built and tested.

GENERAL DESIGN

The optical design philosophy for the TMT is that the mirror should be capable of producing images of .1", have over 95% of the optical error budget devoted to tolerances of the optical elements (i.e., make a perfect control system), and have the primary mirror be coherent in the IR and visible. Figure 1 shows the scale of an f/2 ten meter telescope with a segmented primary.

The primary is made up of 1.4 meter diameter hexagonal segments (fig. 2), with the sensors and actuators mounted on the reverse side. The segment position is defined by six parameters (fig. 3). The translations along the X and Y axis and rotation about the Z axis are constrained by a radial support post. The optically important motions are the two tilts in the X - Y plane and the displacement along the Z axis.

Measurement of adjacent mirror edge displacements with displacement sensors located as shown in the insert of fig. 2 gives both the segment displacement with respect to its neighbor and the tilts, through the moment arms between sensors. This requires only a large number of one type of sensor to measure displacements normal to the mirror surface. The ideal sensor should be insensitive to motions in any other direction.

The required sensitivity of the sensor is set by the coherency and image resolution requirements of the mirror. To maintain a coherent wave front, adjacent segments should not have displacements greater than 50 nm. A 50 nm r.m.s. displacement of an edge for a 1.4 meter segment size produces slope errors which degrade the images to .1". A 50 nm r.m.s. measurement requires a sensor noise level less than 16 nm r.m.s. equivalent signal. Figure 4 shows the effect on image quality versus wavelength for optically perfect segments and two sensor noise levels. The positioning accuracy of the actuator has to complement the sensor noise level requirements. The sensor and actuator must have 3 mm or more complience range to accommodate the expected mechanical deformation. For a 3 mm range, 2×10^5 increments will be required to achieve the desired accuracy.

The bandwidth of the control system will be limited by the natural resonate frequency of the mirror cell, which is expected to be greater than 20 Hz. Wind loading will set the bandwidth requirements for the control system since gravitation and thermal deformation of the mirror cell will vary slowly. Unfortunately, the effects of wind loading on the mirror cell are not known in detail and will depend upon the as yet undefined dome. To resolve this question a study is underway to obtain energy density spectra of the wind pressure on various mirrors for different orientations of domes and winds.

The overall stability of the mirror figure will depend entirely on the stability of the sensor. This sensor system places the detectors on the back of the mirror segments. It is critical that the mirror material behavior not effect the sensor location. Proper specification of the expansion coefficient of segment glass eliminates this problem [2].

Since the sensors will have a finite thickness, the material they are fabricated from should have mechanical characteristics similar to the mirror material. The sensor system (i.e., mechanical and electronic) should be intrinsically stable at the 16 nm level per day, preferably longer in order to avoid frequent recalibration of the zero set point for each sensor.

Table 1 lists the general design requirements for a sensor and actuator for a segmented mirror. This list is not exhaustive but should provide a basic outline of desirable design goals. It was with these goals in mind that the U.C. design was developed.

DISPLACEMENT DETECTOR

There are many measuring techniques, i.e., optical, inductive, and capacitive, which have sufficient sensitivity to measure 20 nm displacements. But, a capacitive bridge measurement technique was chosen for the displacement sensor because it is the only method found so far which meets the aforementioned requirements.

Figure 5 shows an electronic block diagram of the detector. The detector is a balanced capacitive bridge with precision ratiometric impedance measuring electronics. The bridge is driven with a complimentry 40 Khz sine wave on both sides of a movable common electrode. The two sensor pads are summed together at a node where the difference signal is fed into a charge sensitive preamp. The difference signal is then amplified in a bandpass amplifier which drives a precision sychronous rectifier. The output of the rectifier is proportional to the displacement of the bridge. The detector can be electronically nulled, so zero output from the rectifier corresponds to the desired segment position.

The drawing in figure 6 shows the way the test detector is assembled. It is made of zero expansion glass the same as that of the segments. An evaporated metallic coating with the proper pattern covers the three major sensor pieces. The assembled sensor in fig. 7 has the driving and nulling junctions attached. A constant force mounting consisting of threaded rod and springs hold the sensor together.

The results of an initial week long test (fig. 8) show the detector system is stable to 20 nm. The short periodic oscillation corresponded with the cycling of the laboratory heating system. The large step at 68 hours occurred at 7:30 Monday morning when the building thermostat was turned up. The temperature changed 15°C during the test. The thermal sensitivity was due to an error in the metallic coating which extended under the spacers and to drift in the electronics. The electronics will normally be in a temperature controlled box.

The detector has an equivalent noise of less than 1 nm r.m.s. for a 100 Hz bandwidth. Currently, tests are in progress on a recoated sensor and improved electronics. Preliminary results show less than 5 nm/week drift. Even the initial test detector meets the necessary design goals for a displacement detector.

A detector which is usable on a segmented mirror has been designed (fig. 9). It has a pivoting central electrode for easy removal of the mirror segments and a flexible hermetically sealed rubber boot to permit washing of the mirrors.

DISPLACEMENT ACTUATOR

An actuator for the proposed segmented mirror will have to carry a 150 Kg load and give a 20 nm incremental resolution over 3 mm range. The motion of the actuator will also have to be smooth and monatonic at the 20 nm level. A wide variety of displacement mechanisms (hydraulic, pneumatic, piezoelectric, peristallic, lever, screw and various hybrid types) were investigated. The device which meets the requirements is a recent addition to the roller screw family, a precision recirculating planetary roller screw (fig. 10).

This type of roller screw uses planetary rollers as the roller bearings. The planetary rollers are reset sequentially one pitch length each turn by the differentials at the ends of the nut. The use of rollers instead of balls gives this type of screw greater than three times the load capacity of an equivalently sized ball screw. The nut advances one pitch length per revolution of the screw requiring an angular setability of $25''$ on a 1 mm pitch screw for a 20 nm displacement.

Seven screws of 12 mm diameter and 1 mm pitch were purchased [(3)] and tested using a fixture incorporating an interferometer to measure displacements. Three different lubricating methods for the screws were also tested. The method of lubrication is very important because the screw will be in effect dithered in the actuator. Dithering will squash out any wet lubricant from between the bearing surfaces permitting metal-to-metal contact and thereby causing failure of the screw. All the screws were degreased to remove the factory applied grease. Two of the screws were treated with tungsten disulfide [(4)], a dry lubricant. Tests were run with these two screws in a dry state. Then all the screws were tested lubricated with a synthetic oil. The screws, two dry and all of them wet, had smoothness and monotonicity better than 15 nm and slipstick less than 15 nm. Figure 11 shows the response of a screw when step functions of 12.5 nm increments were inputed. The excellence of these measurements indicated that the screw will work as the actuating mechanism for a segmented mirror.

A screw has been incorporated into an actuator whose block diagram is shown in figure 12. Figure correction commands come from the mirror control computer. The correction is calculated from measurements of the displacement detectors. A drive signal for the torque motor is generated from the correction signal. A shaft encoder measures the motion of the screw. In between update commands, the local control loop, (i.e., microprocessor, torque motor, encoder) maintains the screw in the last commanded location.

The actuator is composed of an inner housing assembly, shown schematically and partially disassembled in figures 13 and 14. The inner housing contains the precision components of the actuator—the roller screw and axial thrust bearing as well as the torque motor, limit switch/dead stop, and inner diaphram. The 63.5 cm long outer housing shown in fig. 15 and 16 contains the inner housing, the preload spring, encoder, and torque motor drive electronics. The entire unit is hermetically sealed. Figure 17 shows the assembled unit. Work is currently underway to make a single element servo loop by tying an actuator to a sensor.

I would like to close by showing how the back of our proposed segmented mirror might look. Figure 18 is a top view with the segments transparent. Figure 19 is the same view in perspective from below. One mirror has a complete set (12) of displacement sensors along its edge. The nine mirror support points transmit their load through three wiffle trees to three actuators. The alt-azimuth mounting of the telescope permits the use of a counter balanced radial support post in the center of the mirror to take up the radial mirror load. Sufficient room is present between the mirror cell and mirror back to permit good access for servicing.

I have given a list of requirements for sensors and actuators and briefly described the system I have been working on. Even though tests of elements of this control system have given excellent results, a mirror control loop test should be performed soon to verify the system model. We are currently trying to obtain funding for a two 1.4 meter mirror test system which incorporates one movable mirror with three actuators and four sensors.

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REFERENCES

1. Nelson, J., "Control Systems for Segmented Primary Mirrors" Proceedings of the Conference on Optical and Infrared Telescopes for the 1990's, Tucson, Az., Jan. 7 - 12, 1980.

2. Gabor, G., "Position Sensors and Actuators for Figure Control of a Segmented Mirror Telescope", SPIE Proceedings, Vol. 172, Instrumentation in Astronomy III, Tucson, Az., Jan. 29 to Feb. 1, 1979.

3. La Technique Integrale Division of SKF, Chambery, France, Model PVCZ 12X1 R1 roller screw -- U.S. representative, The Prideaux Company, Rancho Palos Verde, California.

4. Tungsten disulfide treatment by Northwest Dicronite, 1291 Terra Bella Avenue, Mountain View, California 94040.

TABLE 1

General design requirements for a segmented mirror and its displacement detectors and actuators.

Optical

1) a fully filled aperature
2) .1" resolution in the visible and diffraction limited at 10 microns
3) coherent surface in the visible
4) a constant surface emittence for IR work
5) 1% or less of the incoming energy added to the diffraction pattern due to the cracks between mirrors
6) no stray light from the figure control detectors in front of the mirror
7) no heat sources or long thermal time constant elements to disturb seeing

Mechanical

1) elements be easy to remove or stow
2) attachments to the mirror be light weight and have non-hysteretic joints
3) be modular in design to aid "mass production" and field repairability
4) have a low number of different modules
5) make heat removal from active components easy
6) have a lifetime of 40 years or more with annual maintainence

7) have sufficient complience in the control hardware to accommodate all deformations

8) the sensor have long term stability

Electronics

1) be modular in design

2) have a self-failure detecting system with fail-safe feature

3) be an over constrained system with sufficient redundency to permit maintainence to be postponed until scheduled periodic times

4) be immune to normal electrical noise

5) have a programmed shut down in event of power failure

6) be easy to calibrate

7) possess a bandwidth great enough to correct the highest disturbing frequency

Environmental Requirements

1) operating temperature range + 25°C to - 30°C

2) barometric changes of .1 atmosphere

3) humidity 0 - 100%

4) operate in wind velocities up to 80 Km/hr

5) be unaffected by dust and biological assault

6) resist effects of lightning

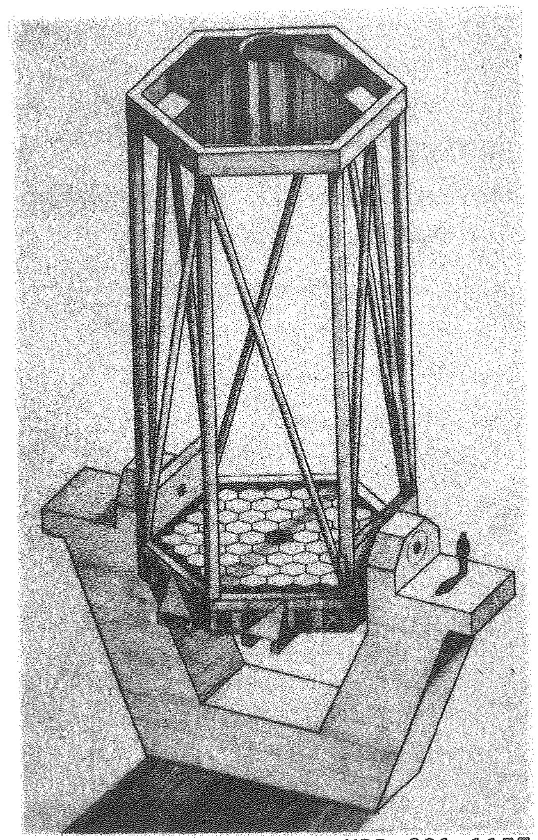

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Fig. 1. Segmented Ten Meter Telescope

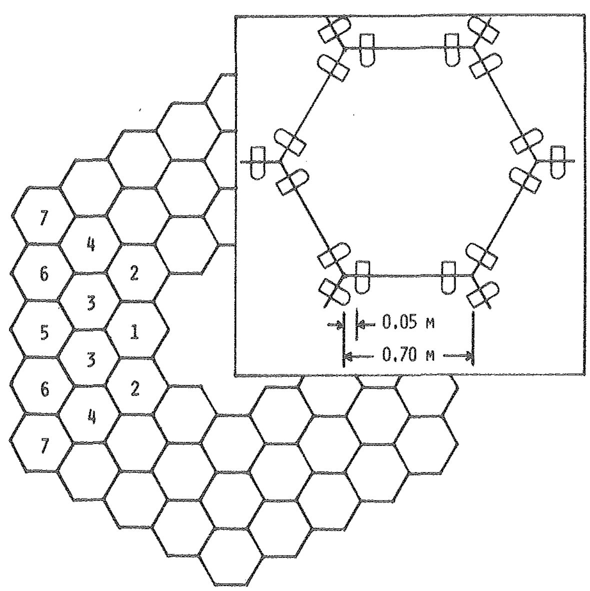

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Fig. 2. The primary mirror, with the different mirror types labled. The inset shows the approximate location of the displacement sensors on a segment

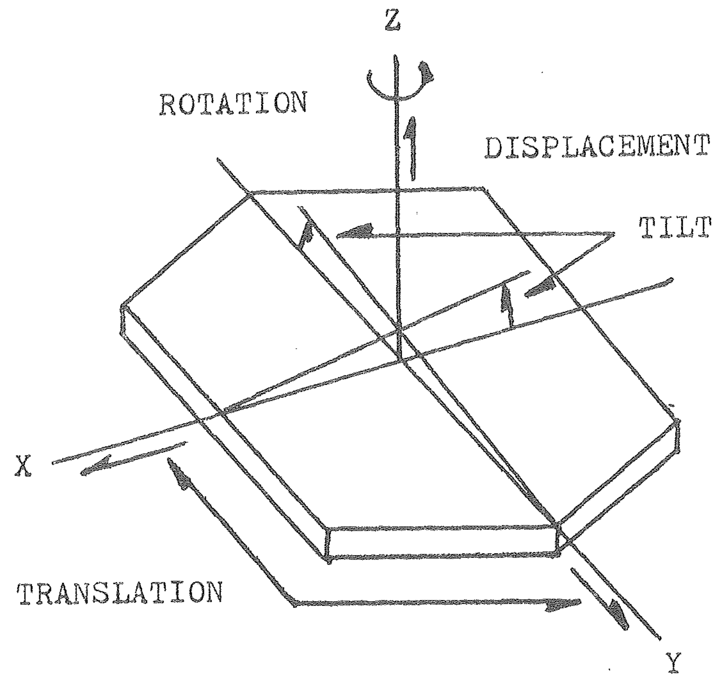

Fig. 3. The six motions of a segment

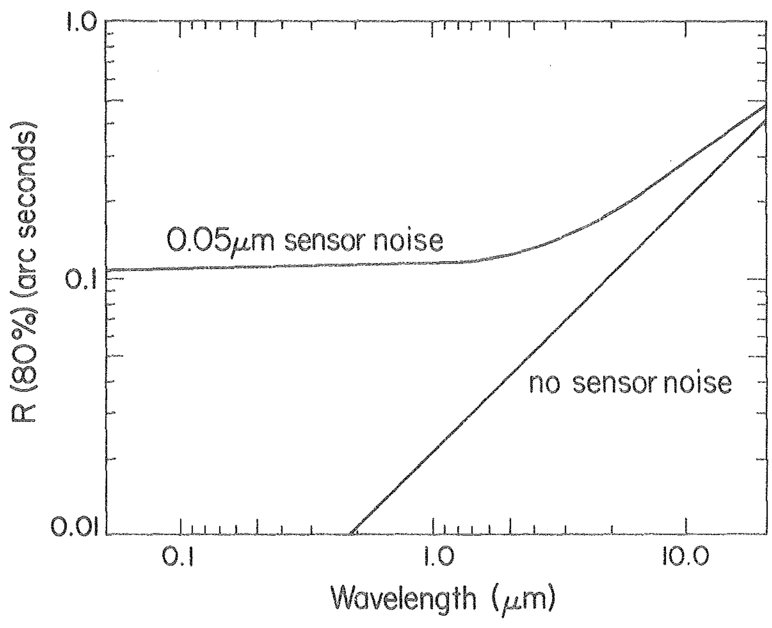

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Fig. 4. Effect on image quality versus wavelength for optically perfect segments and two sensor noise levels

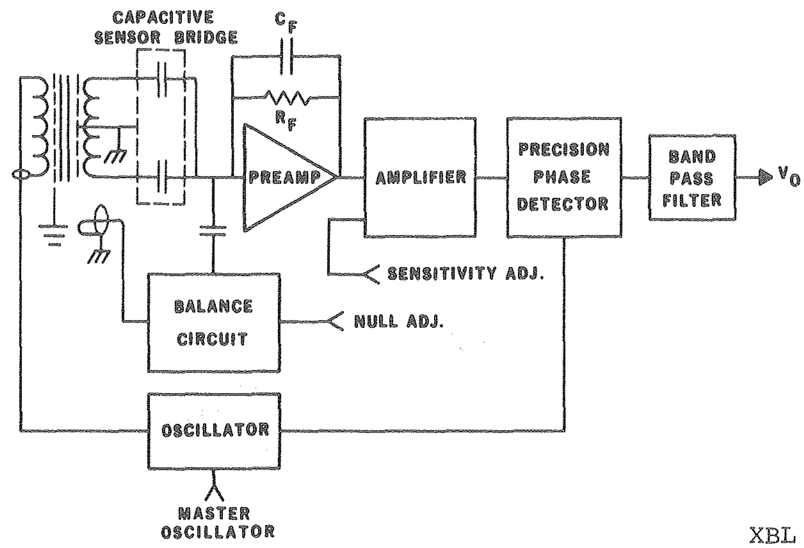

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Fig. 5. Block diagram of displacement detector

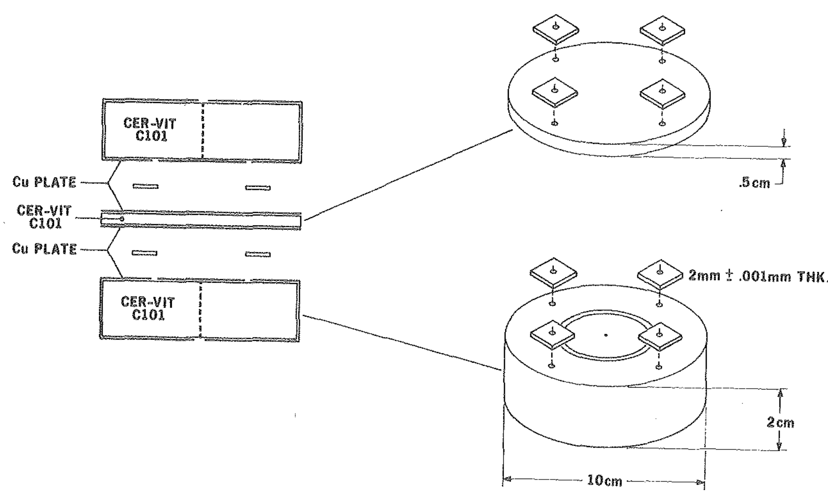

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Fig. 6. Mechanical configuration for test displacement sensor

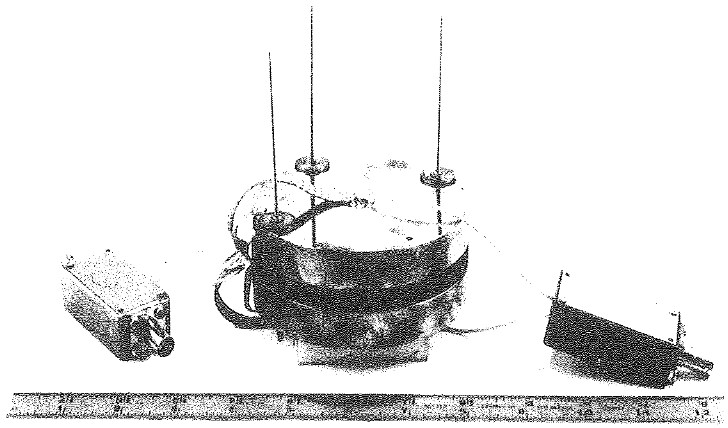

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Fig. 7. Test displacement sensor

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Fig. 8. Test of displacement detector stability with time

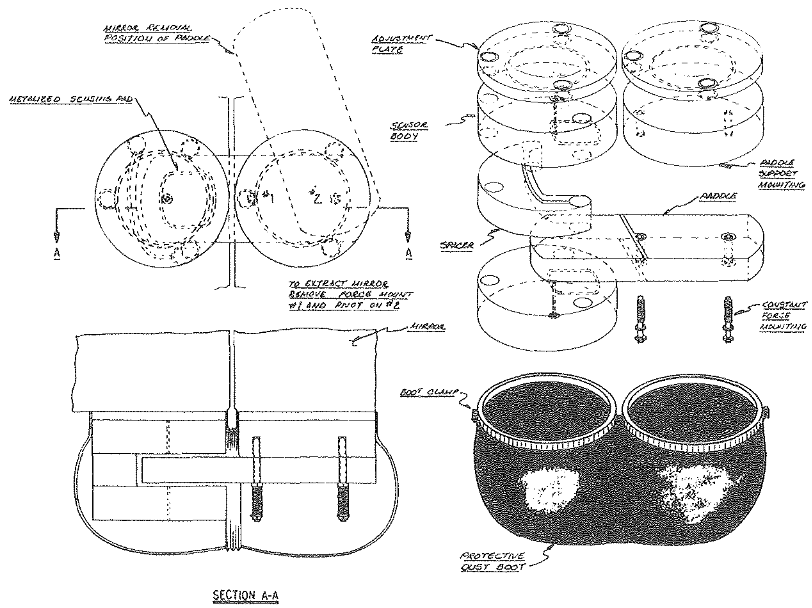

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Fig. 9. Displacement sensor

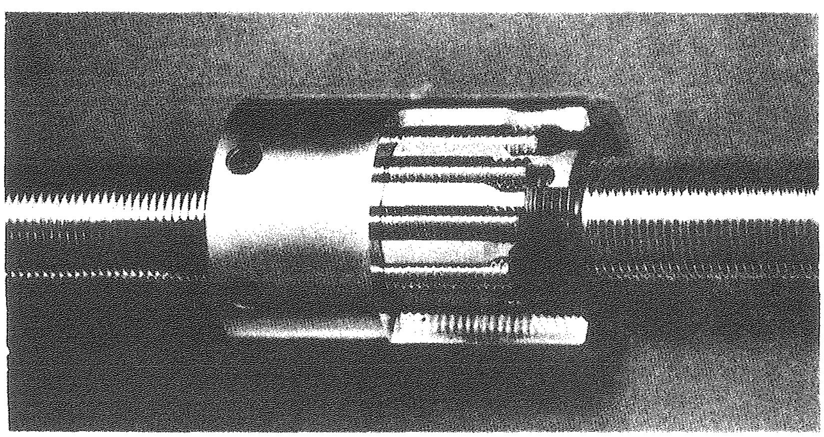

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Fig. 10. Planetary roller screw

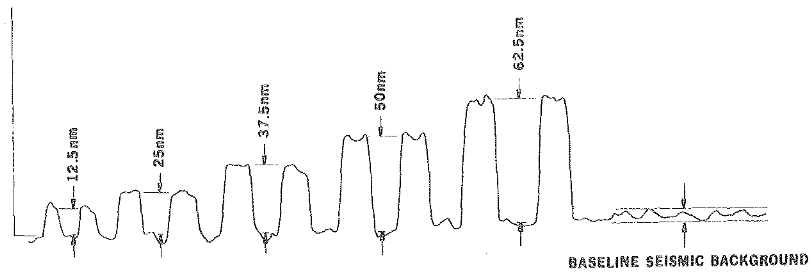

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Fig. 11. Roller screw displacement response for incremental step input

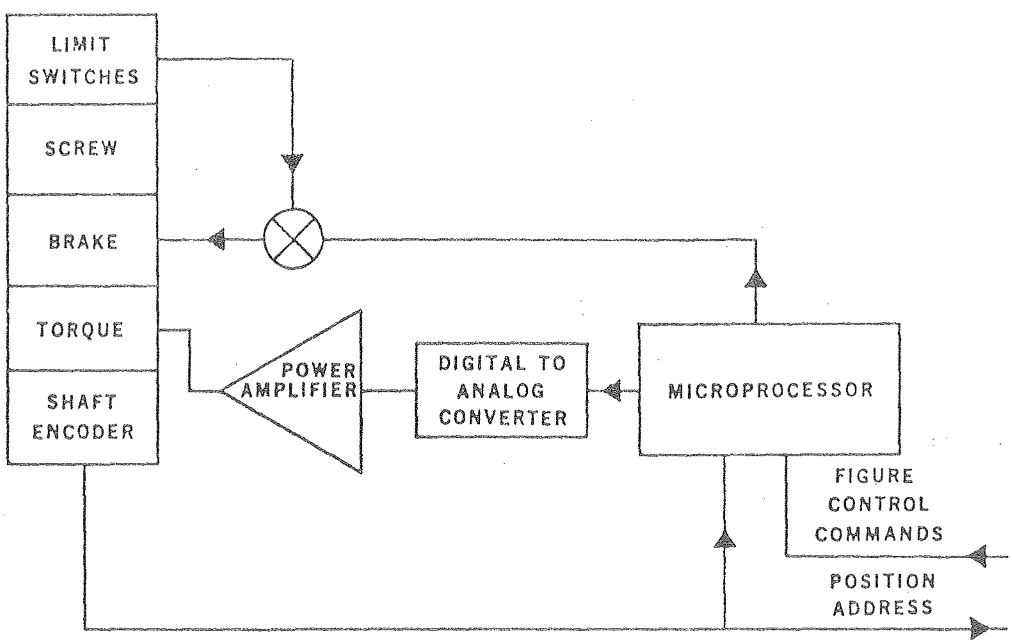

Fig. 12. Block diagram of displacement actuator

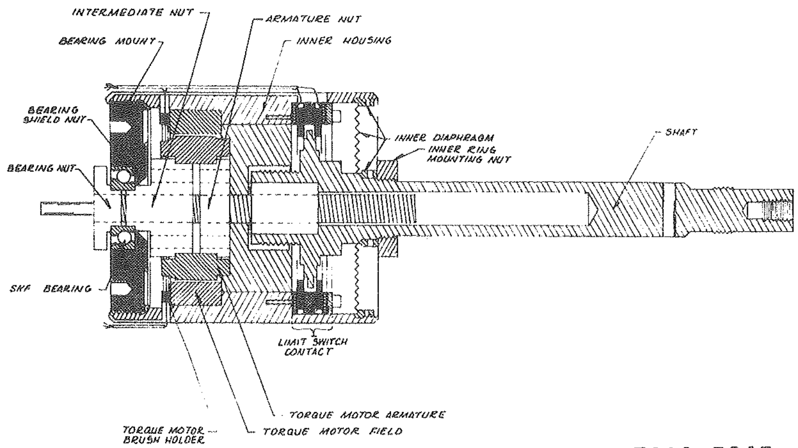

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Fig. 13. TMT precision servo actuator inner housing assembly

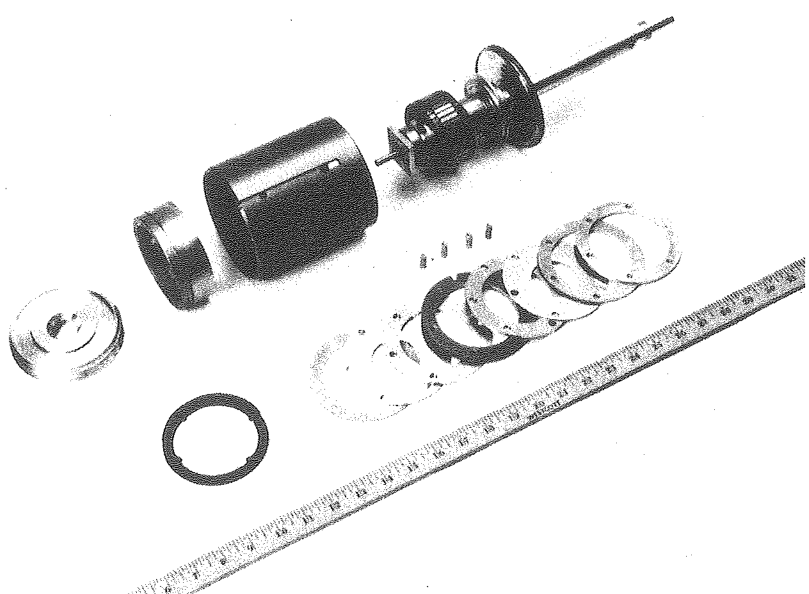

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Fig. 14. Partially disassembled inner housing assembly

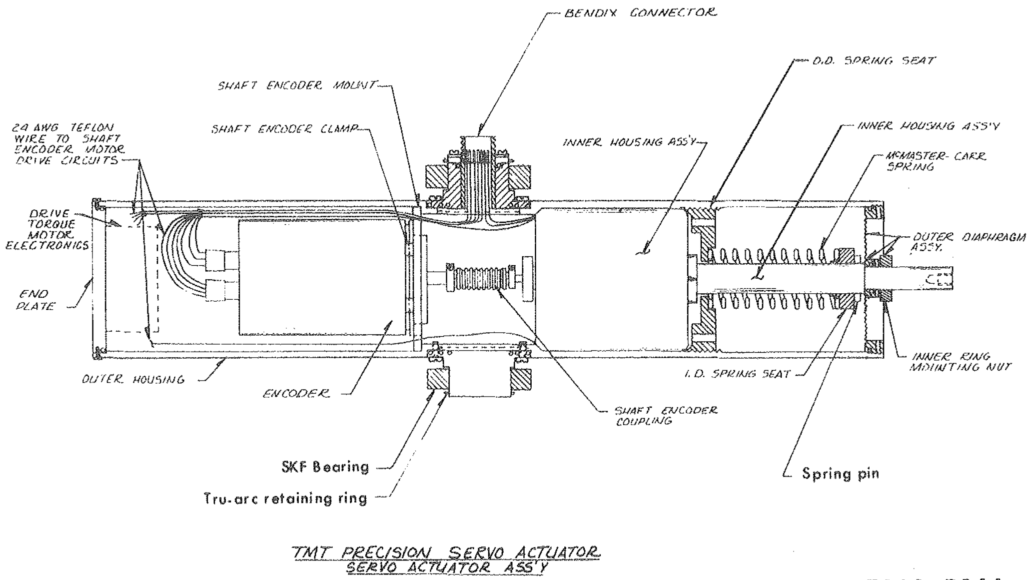

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Fig. 15. TMT precision servo actuator assembly

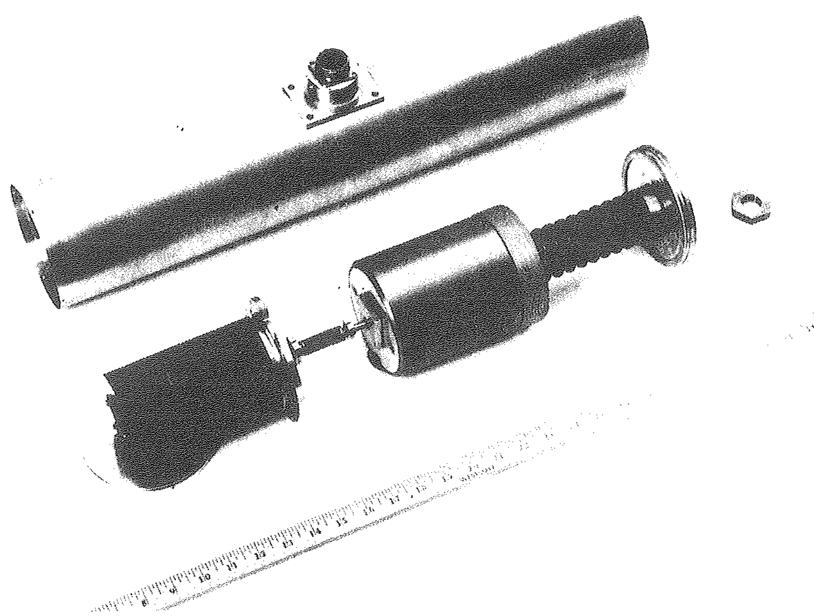

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Fig. 16. Disassembled outer housing

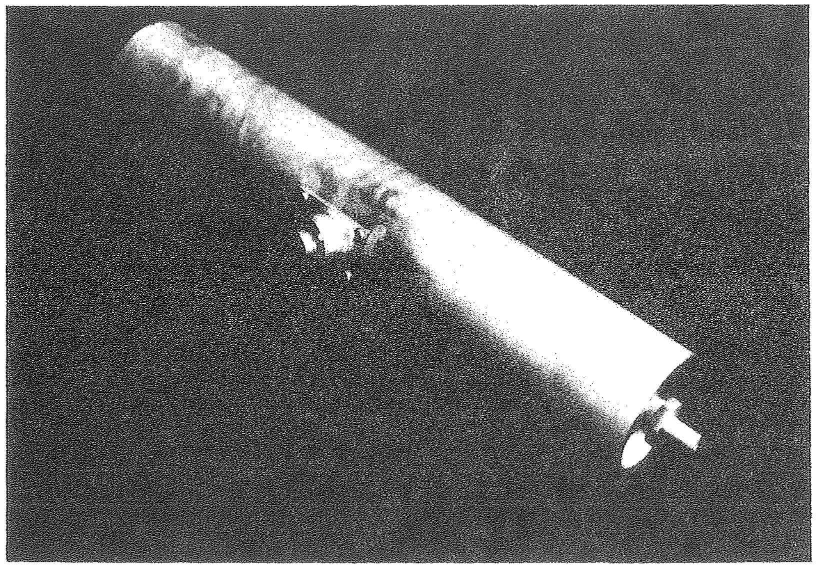

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Fig. 17. Assembled displacement actuator

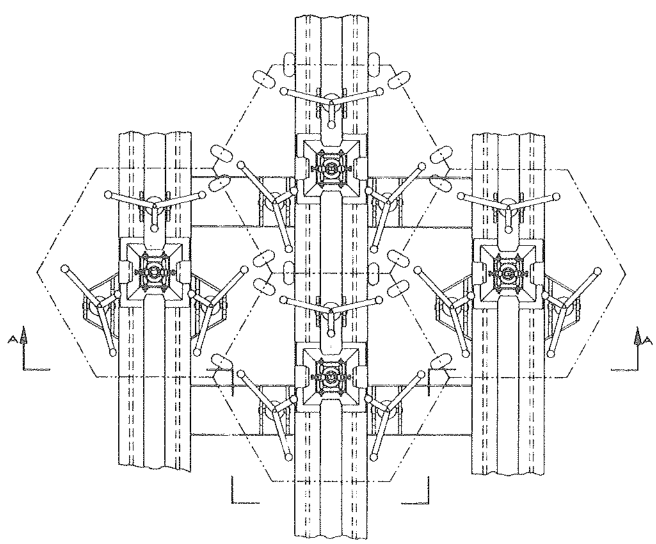

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Fig. 18. Top view of support structure

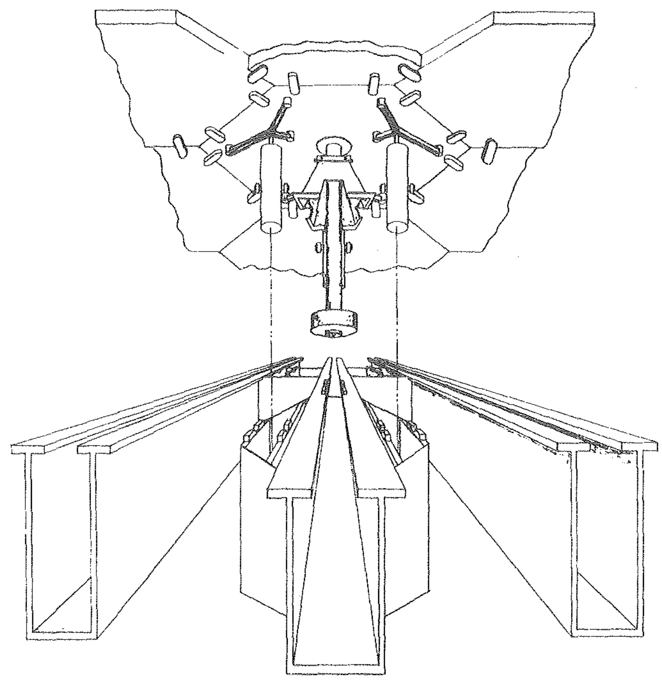

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Fig. 19. Perspective of support structure