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ANTENNA TRACKING MECHANISM FOR GEOSTATIONARY SATELLITES

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ABSTRACT

This paper describes the design and development of a continuous duty cycle antenna tracking mechanism (ATM) for geostationary communications satellites. This paper presents the FACC requirements for an ATM and describes the development mechanism designed and built for the program. The mechanism mechanical configuration and component performance is documented along with its launch and operational constraints. The proposed development tests and the results of computer simulations are discussed. The advantages of this mechanism are its simplicity with inherent reliability, low mass, high stiffness, and ability to accurately point a wide range of antenna sizes.

INTRODUCTION

Communications satellites are tending to use higher frequencies and narrower shaped antenna beams. For these beams to be practical, the antennae have to be oriented accurately at their ground targets. Typically, the allowable pointing error is 10 percent of the beam width, although this depends largely on the gain slope at the edge of the coverage area.

FACC has identified a future requirement for an ATM to compensate for body motions, thermal distortions, and alignment errors of its three-axis communications satellites. The mechanism is to operate continuously using a RF sensor for control loop position feedback.

The critical performance requirements for the mechanism are as follows. The required level of reliability has not been identified, although it should be as high as possible to prevent a mission failure.

Reflector diameters--1.0 to 4.0
Boresight tracking range--$\pm 2.0°$
Maximum beam-pointing error--0.02°
Maximum tracking rate--0.1°/sec
Control loop--RF sensor
Duty cycle--Continuous
Lifetime--10 years

Mass, height, and power consumption to be a minimum.

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MECHANISM DESIGN

The development model mechanism is shown in Figure 1. The design consists of three basic units: linear motor, position sensor, and gimbal assembly. The gimbal assembly connects the antenna interface plate to the base plate and permits small angles of rotation about two orthogonal axes. Linear motors and linear position sensors in each axis provide the torque to rotate the reflector and sense its angular position.

There are no wearing surfaces or sources of friction in the design and the gimbal pivots act like torsion springs and do not require lubrication. This ensures high reliability and long operational life. As the design does not contain wet lubricants, and because the moving components enjoy substantial clearances the mechanism can operate in relatively severe thermal environments.

Because of the high axial and radial stiffness of the flexural pivots the gimbal is very stiff axially and in torsion about the unused axis. Each pivot is rated at 2000 N (450 lbs) radial load capability, and even though the full capacity is not intended to be used, it allows simple caging systems to be used for protection during launch.

MECHANISM OPERATION

When a constant voltage is applied to a motor the gimbal deflects a proportional angle and stays there. When the voltage is removed the restoring pivot torque returns the gimbal to its datum position.

The control system is designed to reduce the existing pointing error between the target and the antenna boresight. Dedicated electronics have not been built for the development model mechanism, but real-time computer control is to be used to test the mechanism and its control techniques. For a flight mechanism the control system is provided with RF sensor data and LVDT data (reflector to spacecraft position) in each axis. Only RF data are required to maintain a stable control system, but further development tests may show a system improvement should LVDT data also be used.

Usually, LVDT position data are only required for telemetry purposes and as a back-up control loop for periods when RF data are not available (i.e., preRF acquisition, beacon failure, and excessive body motion.

LAUNCH CONFIGURATION

The ATM may be used for body mounted or deployable reflectors. Figure 2 shows both launch configurations and their caging systems.

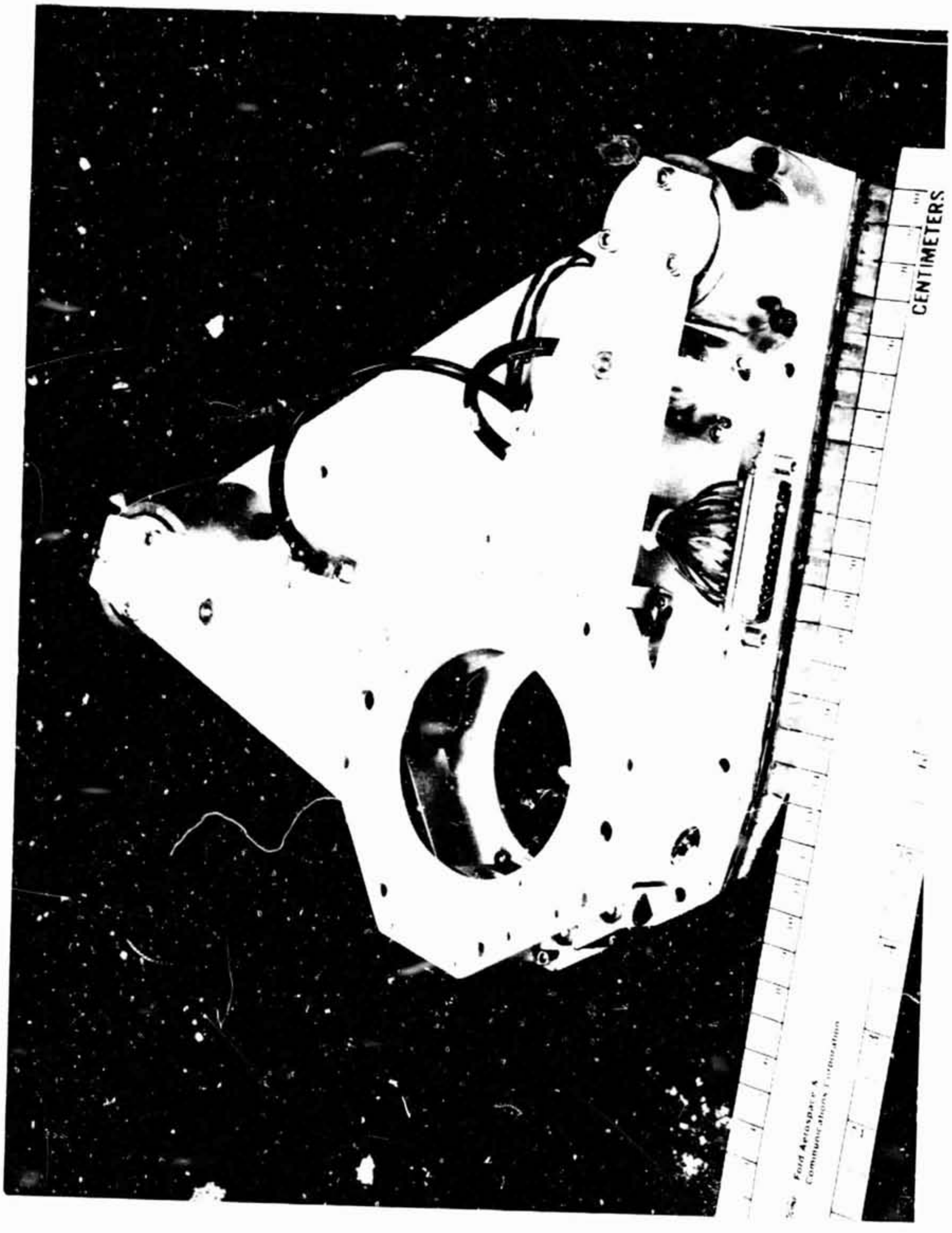

Figure 1. Development Model Mechanism

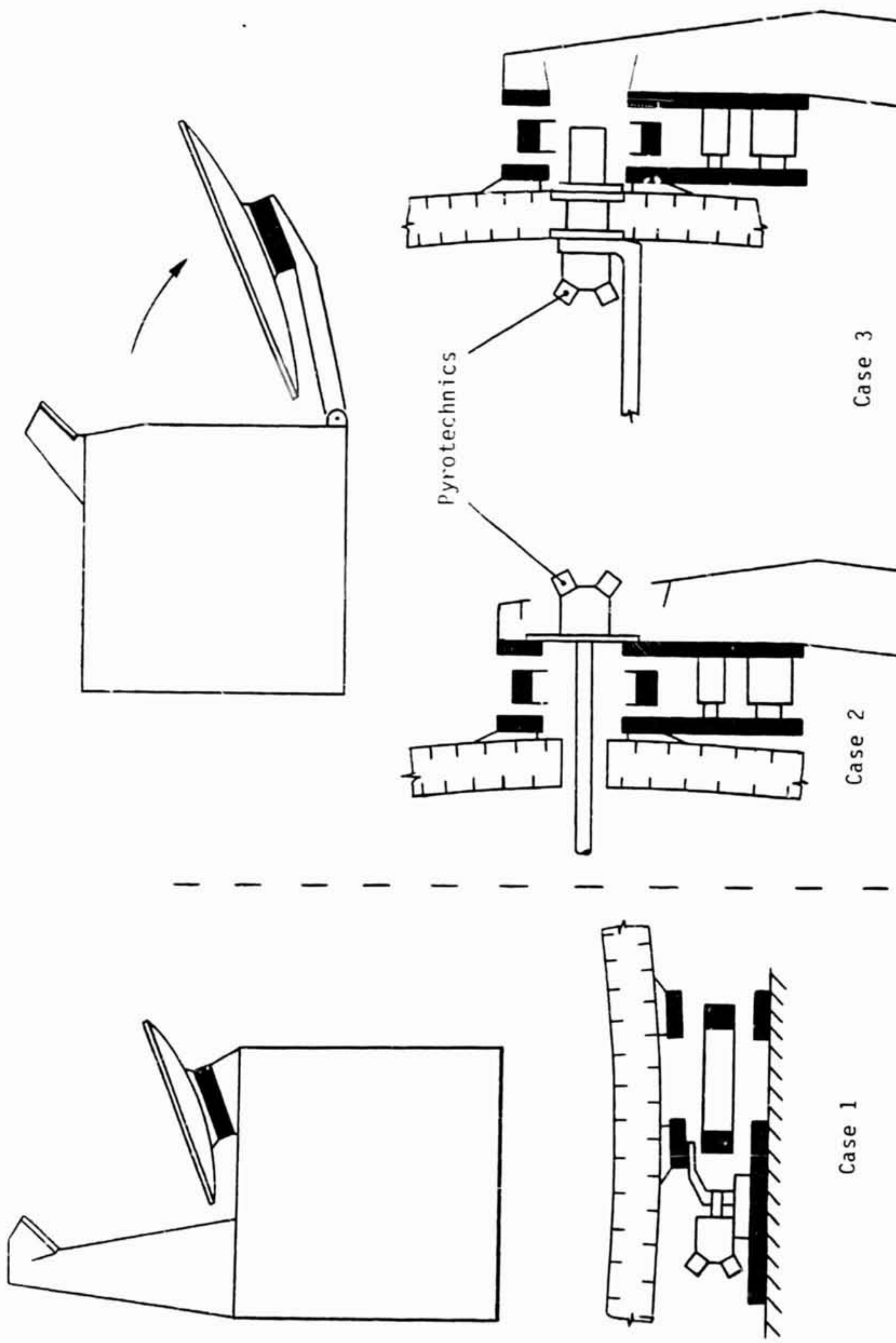

Figure 2. Launch Caging Configuration

Body mounted reflectors are generally of small diameter (1.0 to 2.0 m), and so a pyrotechnic caging device mounted between the antenna interface and the base plate (Case 1) would be sufficient to restrain the reflector. Larger reflectors may require a restraint at a greater radius, with the attachment on the reflector.

Most large reflectors (>2.0 m) will be deployed on a boom from the side of the spacecraft body. Several hold-down configurations are possible with this. The mechanism can be caged to the spacecraft and the reflector snubbed against the body sidewall (Case 2). Or the reflector can be caged and the mechanism either caged or free to rotate (Case 3). The central hole (6.25 cm diameter) can be used for access to the mechanism base plate through the reflector.

It is desirable for both launch and operation that the reflector is mounted centrally on the mechanism with its c.g. directly over the axes of rotation.

GIMBAL ASSEMBLY

The gimbal assembly is constructed around four double-ended flexural pivots. The center section of each pivot is clamped into the gimbal frame and the pivot ends are clamped into supports. Two supports connect the gimbal to the base plate to allow one axis of motion, and the other supports connect it to the antenna interface to create the orthogonal axis.

The pivots are designed to flex through an angle of $\pm 15°$, although interference between the motor components occurs at approximately $\pm 2.5°$. The designed ATM operating range is $\pm 1.5°$.

LINEAR MOTOR CONSTRUCTION

Each axis is driven by a dc linear motor, which is sectioned in Figure 3. Over the mechanism operating range the motor components are noncontacting. Within each motor housing there are redundant windings, effectively giving two motors in each axis. It is intended that only one winding be energized at any instant. The motor core contains two rings of radially oriented permanent magnets, with each ring positioned to be axially coincident with its respective stator winding. Although there are two magnet rings there is only one magnetic circuit, which uses the inner stationary iron piece and the outer stator housing as the return paths.

position. This allows a maximum force of 9.0 N for a 15 Watt input at 20 Vdc.

As the gimbal and motor core are deflected from their datum position the force produced for a given power input decreases. Over the motor operating

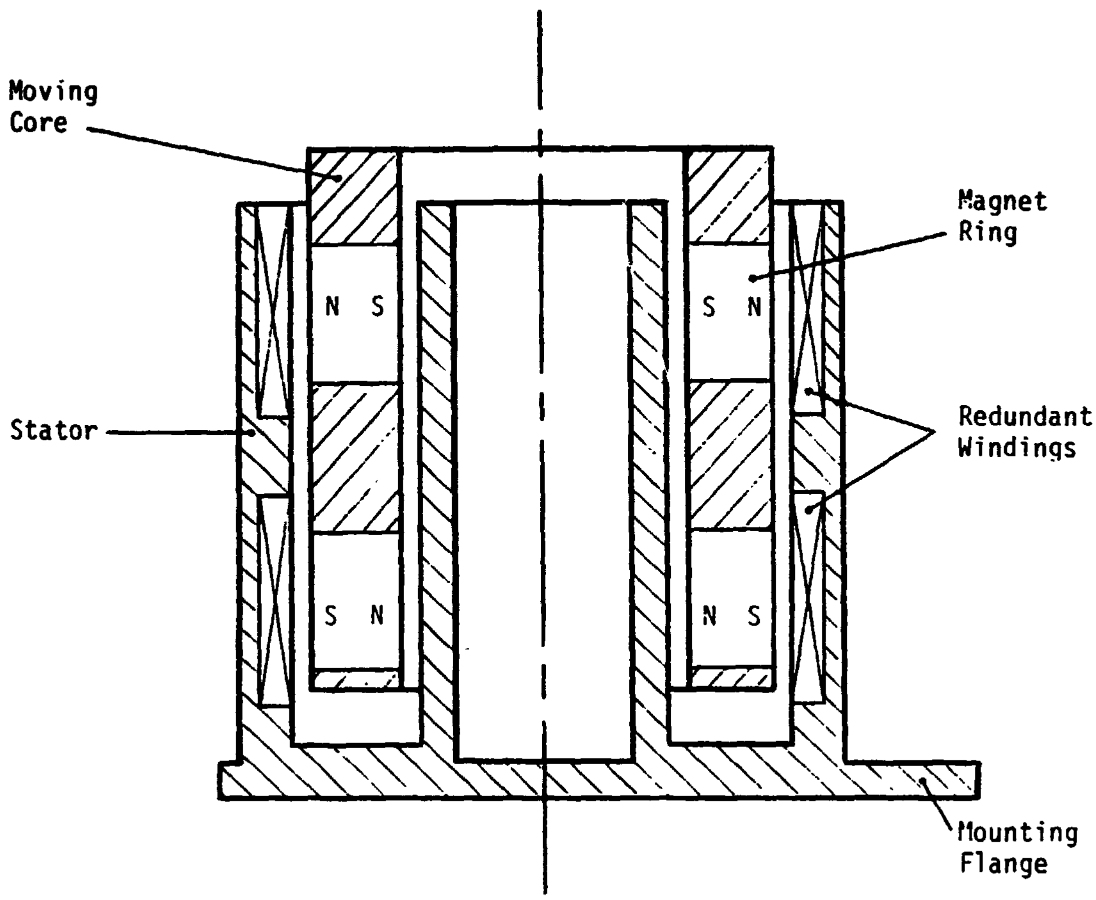

Figure 3. DC Linear Motor

range of ± 3.8 mm the nonlinearity should not be significant to the control system. The slightly angular motion of the core within the stator housing does not appear to cause significant performance degradation.

POSITION SENSOR

The attitude of the antenna relative to the datum position (or spacecraft) is measured by a linear variable differential transformer (LVDT) in each axis. Each LVDT is powered by a signal processing unit, which drives the primary winding with a 2.5 KHz sine wave. An induced current is created in the secondary coils by the high permeability core. From the difference in magnitude of the secondary currents a linear position output ($\pm$10 Vdc) is derived. The stator and core are noncontacting and do not cause friction.

CALIBRATION OF MECHANISM

The computer program which controls the motion of the mechanism requires the input of certain performance parameters. To determine these values, the mechanism is to be calibrated under steady-state conditions.

The power off datum position (with a 1-g counterbalance) is measured optically for each axis. By applying known torques in each axis and measuring the deflection, the gimbal spring constant will be determined. It is predicted to be 0.10 Nm/°, with a linearity better than 5 percent over the operating range. Measuring the deflection against applied motor current will provide the effective motor constant, which will be slightly less than 2.2 $N/\sqrt{Watt}$, with a linearity better than 5 percent over the operating range.

Because of end-effect losses and relative rotation of the motor components, the mechanism deflection is not entirely linear with applied current. However, it should be quite sufficient for the control system to achieve the required pointing accuracy. If desired, the effects of nonlinearities can be eliminated by programming the control law with a variable motor constant dependent upon the LVDT position data.

TEST MODE AND CONTROL SYSTEM

To perform a fully representative series of performance tests the mechanism would have to be mounted on a three-axis table (preferably six-axis) and an RF (or laser) beam generated at infinity to simulate the ground beacon. However, at this phase of development the much simpler test setup detailed below is adequate. A version of the "back-up" control mode (LVDT data only) is used to test mechanism performance.

The satellite interface is held stationary and the inertia is commanded to follow a moving target. The target is an imaginary point in space, the locus of which is generated by the computer. The angular range and rates are generated such that the mechanism experiences loads equivalent to predicted mission conditions. In reality, the target locus is represented by sine curves and step inputs of varying periods and magnitudes.

To determine the existing pointing error, the LVDT output is compared with the target location. The target track and pointing error in each axis and the time are printed every second to provide a hard-copy record of a test run.

The test computer is loaded with a program to control the mechanism (a flow diagram of the control loop is shown in Figure 4). A line in the program samples LVDT position data every 100 mS, converting it from analog dc voltage to a numerical value. The target position (generated by a line in the program) is compared with the LVDT data and an error value is calculated for each axis.

Using the calibrated mechanism performance parameters, the known inertia and the error values, the control program determines the motor voltages required to correct the existing errors during the next sample period. The computer takes a finite time to perform its task and so a time lag develops in the control loop. If the LVDT's are sampled at T=0 and the control algorithm takes 100 mS to process, then a new motor voltage will be output at T=100 mS in order to eliminate the initial error by T=200 mS. With a 0.2 second time lag it is desirable to predict the motion of the target to improve pointing accuracy. This prediction is performed by the algorithm, as the program stores previous position data for comparison.

It is expected that a realistic spacecraft control system would sample and respond every 60 mS, rather than the 100 mS capable by the current configuration.

Once the new motor voltages have been determined the computer outputs them as ± 20 Vdc analog signals. These are amplified to provide adequate current and then passed to their respective motors. The voltage applied to each motor remains constant during the next 100 mS.

The result is that the mechanism drives the inertia back and forth across its range as it tries to follow the demanded locus as closely as possible.

COMPUTER SIMULATIONS

A computer simulation of the mechanism, the spacecraft, and the reflector interaction has been performed. In this, the mechanism base is given angular and linear disturbances representing thruster firings and this causes the feed/reflector combination to misalign the antenna beam. The error angles

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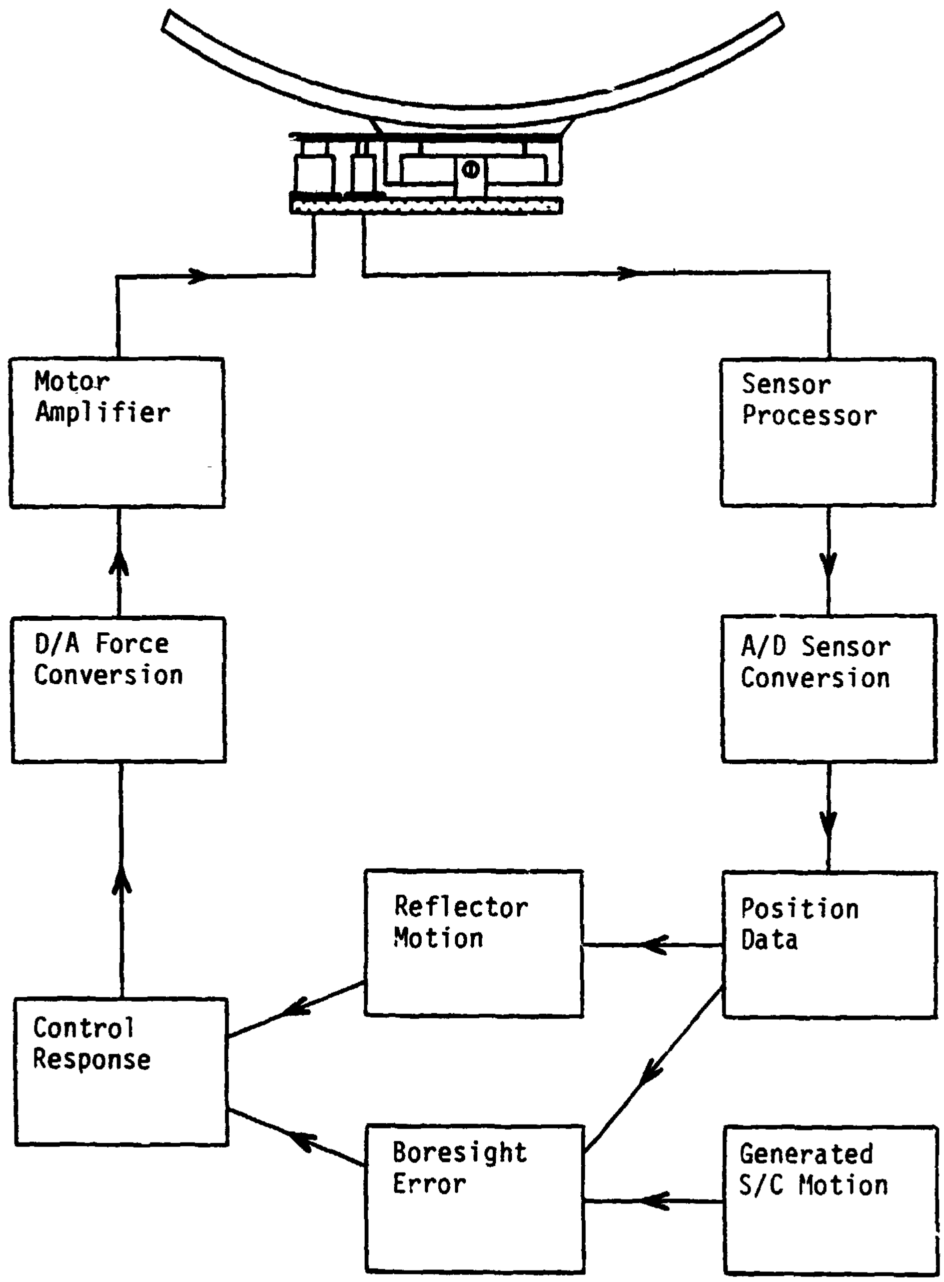

Figure 4. Dynamic Test Control Loop

(representing the RF sensor output) are sampled and a corrective motor force determined. The new force is applied after a suitable time lag and the system dynamics are continuously monitored. Figure 5 shows a typical system response. In this simulation an Intelsat V size spacecraft with a deployed 2-m diameter reflector experiences a 20 N thruster firing. The maximum beam error is 0.02° and the motors draw 0.1 Watts each. After 1.5 seconds the system settles down to an error of 0.001° and total power consumption much less than 1 Watt.

Simulations have been performed for reflectors of 1- to 4-m diameter with inertias of 0.15 to 20 Kgm^2. By varying the control loop gain for specific reflector sizes this large range of antennae can be successfully tracked. Larger reflectors require greater motor forces, while very small inertias allow high natural frequencies about the pivots, and the lag time causes instability.

FURTHER DEVELOPMENT AND TESTING

The tests performed to date have been limited in their scope. The tests that have been performed have been used to confirm the test setup as much as the mechanism. The initial calibration measurements are very encouraging; however, and indicate that the mechanism performance will be as predicted.

Further tests are due to be performed, which will allow the full capability of the mechanism to be realized. These tests, which will include the extremes of inertia and rates of motion, will explore the interactions between the axes and the effects of motor failures and motor/sensor interference.

CONCLUSIONS

Sizing of the mechanism components appears to be excellent. The power, force, stiffness, and sensitivity relationships between the various components are well matched to produce an optimized tracking mechanism. The mechanism promises excellent performance in a remarkably compact and lightweight package.

The use of the computer allows great flexibility in modifying control techniques, although its operating speed needs to be higher.

Recommended design changes for a flight mechanism are to:

- Incorporate redundant LVDT sensor windings; the failure modes of these need to be investigated
- Increase the radial clearances in the motors to allow greater range and easier assembly

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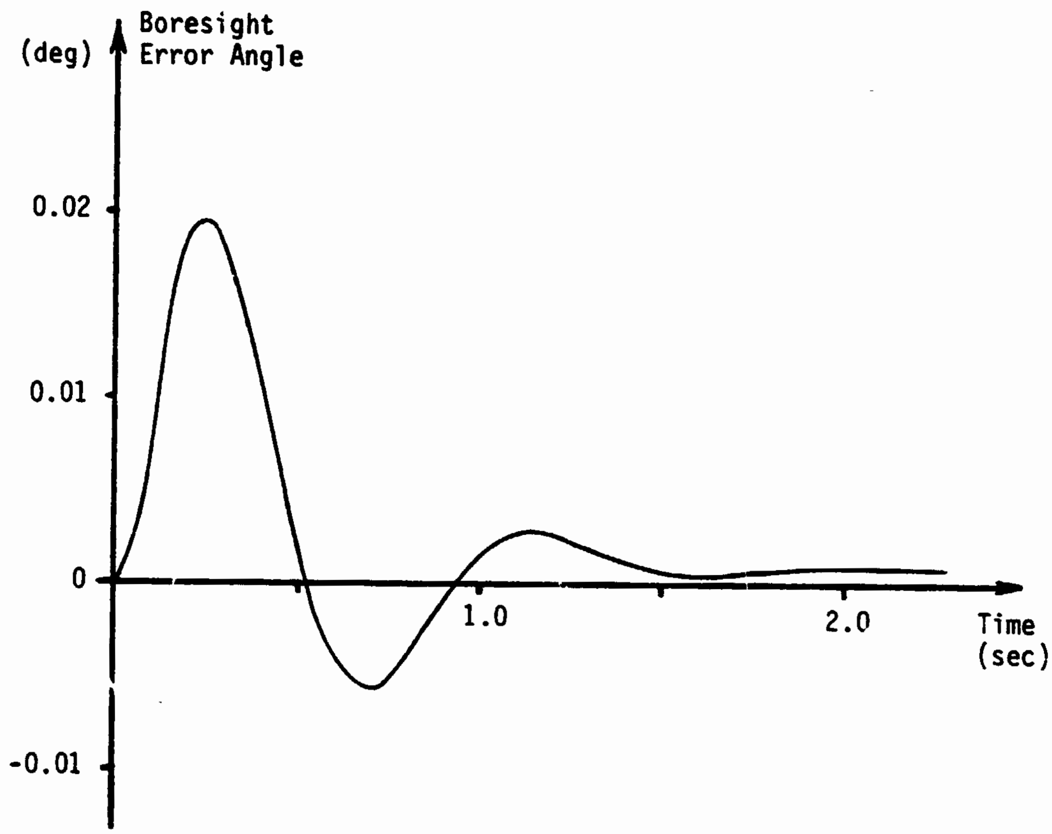

Figure 5. Predicted Boresight Error Response

- Increase structural stiffness, by using stiffer arms and possibly larger diameter pivots (maintaining the current torsional stiffness)

- Reduce mechanism mass by using higher performance materials in the motors and by optimizing the structural components

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