

DEVELOPMENT OF MINIATURE ACTUATOR FOR CRYOGENIC APPLICATIONS

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INTRODUCTION

A goal of Next Generation Space Telescope (NGST) is to detect objects 400 times fainter than what is detectable from other infrared, ground-based telescope systems such as the Keck Observatory or the Gemini Project. The proposed design includes a mirror 8 meters in diameter, much larger than the 2.4 m mirror on the Hubble Space Telescope. NGST will be transported using the space shuttle orbiter or other Evolved Expendable Launch Vehicles (i.e. Titan and Atlas rockets). However, the cargo bay capacities cannot accommodate either the size or weight of a single piece 8 meter mirror. The solution is to build the primary mirror from an adjustable, reflective surface. Tentative designs include a flexible, thick-film like plate or several smaller mirrors, each with a fixed reflective surface shape that can be adjusted independently from other sections. In either case, the primary mirror shape will have to be adjusted using many smaller actuators. These actuators are one of the major challenges of the NGST project and a number of requirements and goals have been set. The requirements are the specifications that are needed for the design to be effective and the goals are the specifications that would aid in the final design, assembly and testing but are not absolutely critical. The key requirements of interest in this design: resolution less than 20 nm, a range larger than 6 mm and the capability to hold position in a power-off condition. Since the intended environment for the device is space, it must operate under cryogenic conditions.

DESCRIPTION OF THE DESIGN

The prototype is designed around a precision 1/4"-80 pitch screw that provides inherent power-off holding when transferring an axial load of the screw through a matching nut connected to ground. The system uses two sets of piezoelectric actuators to provide motion. Using the clamping set of actuators, the screw is locked by pushing the two clamping brass nuts apart. To rotate the screw, the rotation actuators push the rotational nut by pushing against the integrated front endplate (connected to ground). The rotational nut has flexures that allows the nut to rotate about the center of the screw. If the screw is locked by the clamping actuators, the rotational nut will slide on the screw but if the screw is unlocked, rotating the nut will rotate the screw with it. Using a series steps that includes rotating the screw, locking the screw, repositioning the rotational nut and unlocking the screw, the screw will displace axial in small steps. A sketch of the design is shown in Figure 1.

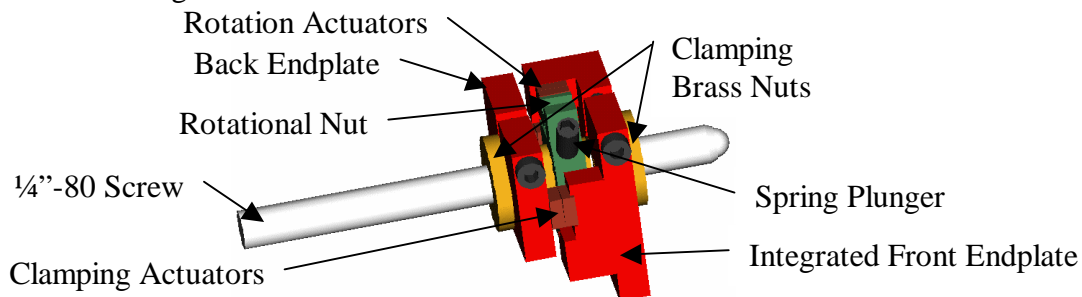


Figure 1: Overall view of the actuator prototype

* Currently at Vistakon, Johnson & Johnson

ACTUATOR OPERATION

Operation of the actuator involves four steps:

- 1) the rotational nut is forced to rotate around the center of the screw by a pair of piezoelectric actuators and it carries the screw along with it;
- 2) the clamping actuators push the front and rear clamping nuts apart increasing the friction needed to rotate the screw;
- 3) the rotational nut is deactivated and it rotates back to its initial position but without the screw;
- and 4) the clamping actuators are released.

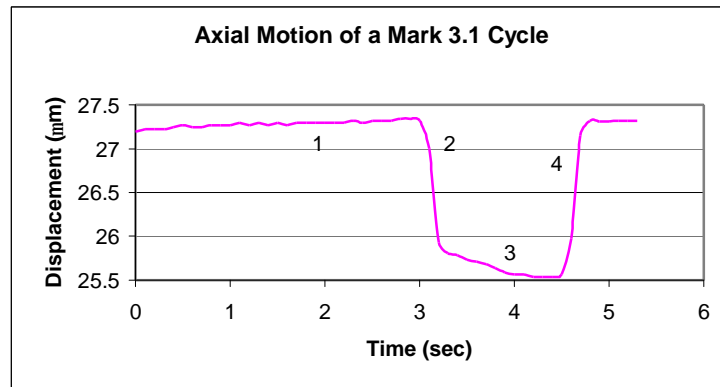


Figure 2: Motion of Mark 3.1 for one Cycle

Each step of the actuator can be viewed in the axial motion of the screw as observed in Figure 2. The first step (rotating the screw) is seen as a small upward sloping motion displacement (1). The next step (2) is to clamp the screw which sends it away from the load as a sharp downward motion of about $1 \mu\text{m}$. This is caused by the clamping actuators pushing the clamping brass apart and increases the axial force on each. The screw/nut interface at the front clamping brass nut is supporting the axial load F . When the clamping actuators are energized, the force on the front nut is increased, and as a result, the nut is pushed away from the load. The third step (3) in the displacement motion of Figure 2 is a result of de-energizing the rotational actuators to move the rotational nut its nominal position. Because the screw is clamped, there should be no axial motion of the screw. However, some motion is evident in Figure 2, which has two possible sources. The first is creep of the clamping actuators; that is, rapid displacement for the majority of their stroke (from step 2) followed by slow creep for the remainder. The continuing downward slope from segment 2 to segment 3 of the cycle could be attributed to creep. Another possible source of motion is radial forces on the screw generated when the rotational nut and modified brass rotate back to their nominal position. If the two tensile forces used to generate the moment and rotate the screw are not equal, then the rotational nut will tend to pull the screw radially. Radial forces on the screw create relative motion between the screw and the clamping brass nuts and move the screw. However, this is unlikely because the clamping brass nuts are firmly locked with the screw during this stage of the cycle. Whatever the source, the prototype displaces a small amount axially during the de-rotation of the screw. The final step (4) in the motion is a large positive jump in displacement upon relieving the clamp load. The positive jump has approximately the same magnitude as the negative jump seen from step 2.

When a series of steps such as illustrated in Figure 2 are strung together, the motion of the actuator can be determined. Figure 3 shows the axial displacement of the Mark 3.1 design using

the ADE 3940 capacitance gage to read the displacement of the screw. The axial load in this case is 0.2 N.

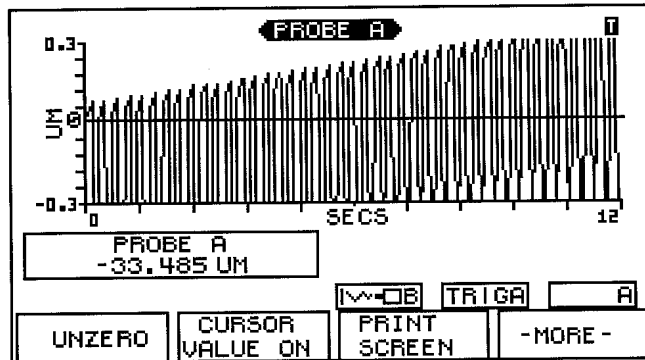


Figure 3: Axial Displacement (0.2 N Preload)

Figure 3 shows displacement of the actuator from 60 nm to 300 nm in 31 cycles or 7.7 nm per cycle. The motion of the screw shows evenly displacing steps. A second test is shown in Figure 4 with a 0.5 N preload on the screw. The added load creates additional friction at the interface between the screw and the front clamping nut that leads to slippage when the rotational actuators are energized to rotate the screw. Consequently, a reduction in displacement is noticed with an average step size of 5 nm/cycle measured from Figure 4.

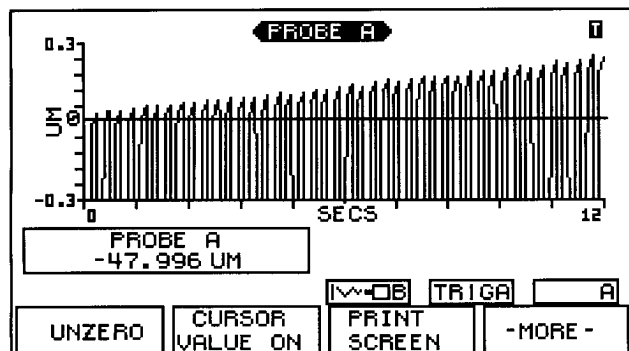


Figure 4: Axial Displacement (0.5 N Preload)

CRYOGENIC PERFORMANCE

To measure the performance of the actuator under cold conditions, the prototype was mounted on a piece of aluminum that rested in a plastic dish filled with liquid nitrogen. The aluminum served as a thermal conductor to extract heat from the prototype to the liquid nitrogen. The dish and the prototype were placed inside of a chamber (150 mm x 150 mm x 100 mm) made from 19 mm R4 closed cell styrofoam. One hole was bored to allow the screw to project outside of the box and another hole to carry wiring as well as a tube transporting nitrogen gas into the chamber. The nitrogen gas was used to purge the chamber for 10 minutes prior to adding the liquid nitrogen to eliminate any water vapor that could condense and freeze on the prototype. A 25 mm diameter hole was cut into the top cover to add liquid nitrogen but minimizing ambient air entering the chamber during the filling.

To measure displacement, a small silicon mirror was attached to the portion of the screw exposed to the ambient air. A laser beam was pointed at the mirror and the reflected light was spotted on a large flat wall 3.53 m from the center of the screw. As the prototype is powered and begins to displace, the rotation of the screw is tracked by the reflected image on the wall. The technique gives the advantage of magnifying the rotation of the screw because a one degree rotation of the screw will cause a two degree sweep of the laser beam. Knowing the distance from the wall to the center of the screw and measuring the change in position of the laser beam on the wall, the angular rotation of the screw can be easily calculated. The axial displacement is calculated from the angular rotation and pitch of the screw.

Cryogenic Testing Procedure

The test procedure began by marking the laser beam on the wall. A stopwatch was started when the compressed nitrogen was started. After 10 minutes, the one inch hole in the lid was uncovered and two cups of liquid nitrogen were poured into the chamber. Every five minutes, a half-cup of liquid nitrogen was added into the chamber. Forty minutes into the experiment, the prototype was started by sending the clamping and rotation signals from controller with a frequency of 1 Hz. The reflected laser beam disappeared due to the condensation and frost buildup on the silicon mirror so the actual minute-by-minute displacement could not be tracked. After 5 minutes, the actuator was stopped having undergone 300 cycles. The apparatus was then left undisturbed allowing everything to warm up to room temperature. As the ice melted off the silicon mirror and the water evaporated, the laser beam reappeared and a final reading was taken the apparatus reached equilibrium with the room temperature; approximately 3 hours was needed for the entire experiment.

Performance at Cryogenic Temperatures

To verify the design of the experiment, three experiments were performed. The first was done at room temperature. The displacement of the laser beam was tracked on a minute-by-minute basis. The displacement was 28 mm/min at a distance of 3.53 m from the wall. Based on the laser path and the pitch frequency of the threads ($317.5 \mu\text{m}/\text{rotation}$), the displacement was 6.7 nm/cycle; that is, it reproduced the results discussed in Figures 3 and 4. The second experiment was performed using cryogenic conditions but the minute-by-minute data could not be captured due to mirror icing. The distance between the start and finish point of the laser beam was measured to be 23 mm or 0.5 nm/cycle. A third experiment was run to verify that the measured displacement of the actuator during cryogenic testing was true displacement rather than thermal drift. This experiment was identical to that of the second experiment but in this case the prototype was never operated. There was some drift during the test and the distance between the start and finish point of the laser beam was 3 mm. However, this displacement is much smaller than the 23 mm displacement of the second experiment described above and thus could be ignored.

CONCLUSIONS

A piezoelectric cryogenic motor has been developed to meet the actuator requirements of the Next Generation Space Telescope. The design objectives for actuator have been met as follows:

- Position resolution requirement of 20 nm with a goal of 10 nm.-The piezoelectric actuator testing has shown that in a cryogenic environment (~80 K)the actuator can take step sizes less then 1 nm/cycle and at room temperature this value is on the order of 10 nm/cycle.
- The stroke of the design must be at least 6 mm with a goal of 10 mm -The actuator is built around a threaded screw and therefore the stroke of the design is governed by the length of the screw minus the length of the chassis. For the Mark 3.1 prototype, the screw length is 65 mm with a chassis length of just under 25 mm. The effective stroke of the design is thus 40 mm, four times greater then the 10 mm requirement.
- Operating temperature range of 20-60 Kelvin with a goal of 20-300 Kelvin -The structure of the design was calculated to have little thermal mismatch in the critical areas of the design (i.e. brass nut on the steel and axial straining of the screw versus the surrounding structure). The same setup was used during both the room temperature testing and the cryogenic testing. While no liquid helium facility was available to test the design at 20 K, the design was tested at 77 K and steps as small as 0.5 nm were measured.
- Capable of holding a load in place with no power supplied to the actuator -This is a major requirement of the motor and allows for a satellite telescope to have large quantities of the motor but not require power to hold position. The design of an actuator around a precision high pitch screw using a threaded nut attached to ground allows for built-in power off holding capability.