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Position Actuators for the Primary Mirror of the W.M. Keck Telescope

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ABSTRACT

The pistons and tilts of the 36 segments of the W.M. Keck Telescope primary mirror are under active control. The mechanical and electronic designs of the actuators used to achieve this control are described along with the performance of the actuators under a variety of tests. In use, the actuators will move in four-nanometer increments. This resolution and the accuracy of the actuator moves are adequate for stabilizing the figure of the primary mirror to the precision required for optical and infrared astronomy.

1. INTRODUCTION

Position actuators[1] for the Keck Telescope primary mirror are adjustable-length devices, three per segment, which connect each segment to its supporting sub-cell. Each is at the vertex of an imaginary triangle on the segment's convex side. The segment is tilted or pistoned by changing the actuator lengths. The telescope's primary mirror consists of thirty six hexagonal segments, each with its reflective surface curved such that, when positioned properly in the array, it becomes part of the optical equivalent of a ten meter hyperbolic monolith. The actuators and their associated control system[4] maintain segment-to-segment alignment as the telescope structure undergoes temperature-induced and gravity-induced deformation. Structural deformation occurs most rapidly while the telescope moves from object to object.

2. ACTUATOR DESCRIPTION

Figure 1 exposes the internal parts of an actuator. A shaft extends from a 10,000-position rotary encoder at the end most distant from the mirror, through the armature of a DC servo motor, and through a support bearing. After the bearing, the shaft has a 1 mm-pitch thread which supplies axial drive to a slide. The slide drives a small piston into an oil-filled hydraulic chamber. At the other end of the chamber, a larger piston drives the output shaft which is attached to the mirror via whiffletrees. The area ratio of the two pistons is approximately 24:1, so 1 mm of axial motion from the slide (resulting from one complete revolution of the shaft) results in ~ 1/24 mm of axial extension by the output shaft (at the mirror). Since each 1/10000 of a shaft rotation is being detected, the smallest controllable increment of shaft extension (output shaft step size) is ≈ 1/24 of 1/10000 millimeter, or approximately 4 nanometers.

The oil in the hydraulic chamber is mineral oil. The large spring in the output shaft barrel adds to mirror load to prevent a reversal of hydraulic pressure when the mirror points below the horizon. The tip of the small piston contains a spring-loaded mechanism to prevent reversing hydraulic pressure when the small piston retracts beyond the output piston's hard stop. The actuator contains a light-gate to generate a signal when the actuator is fully retracted. The combination of this signal and an index mark from the rotary shaft encoder allows us to determine a reference zero point and thereby to precisely reproduce actuator extensions. A small oiler is designed to provide an oil supply to the roller-screw for an extended time. Actuators are designed to operate for at least a year between service, and are expected to have a lifetime of at least ten years.

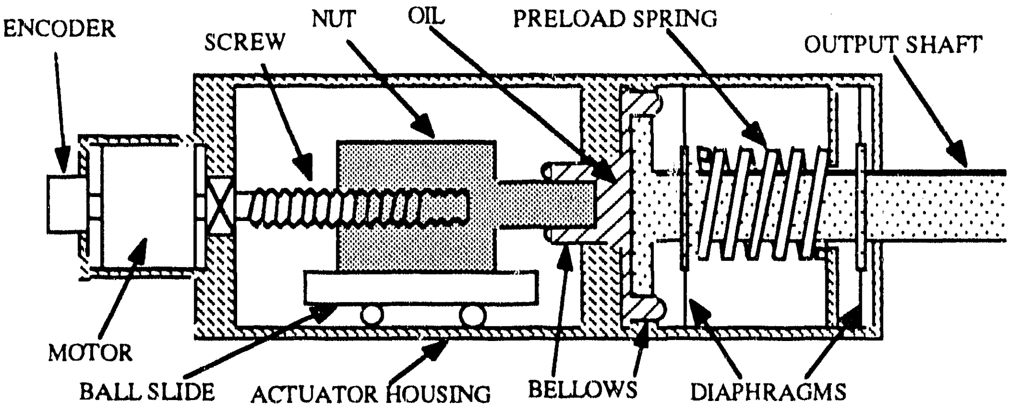

Fig. 1 Internal parts of the actuator

3. REQUIREMENTS AND CHARACTERISTICS

Table I summarizes properties of the actuator.[2] Each actuator will typically dissipate about a half watt. About 75% of this heat comes from the light source in the rotary shaft encoder. About 25% results from resistive losses in the DC servo motor. Encoder dissipation is fixed. Motor dissipation varies widely. Both the motor and the encoder are at the end of the actuator most distant from the mirror to prevent significant glass heating and to minimize heat-induced air motion which might affect seeing.

Step size, as derived from actuator mechanics, is approximately 4 nm. Averaged over many steps, this is the value we observe. Observations show sizable step-to-step variability (tens of percent) but the direction of output shaft motion consistently tracks drive direction. The variability in step size derives mainly from microscopic variations in roller screw pitch and from the mechanics of drive direction reversal.

Routine periodic inspections, tests and service will be done when a mirror segment is removed to be re-aluminized. We expect the operating life of an actuator to be much greater than ten years, because the actuators are assembled under clean conditions, and no moving components are operating close to their mechanical limits. A porous oiler provides a continuous oil supply during operation.

TABLE I. Actuators for the Keck Observatory Ten Meter Primary Mirror

A group of three actuators makes position and tilt adjustments on each mirror segment. Leverage is applied via a roller-screw/hydraulic lever combination.

Physical Characteristics	Dimensions Weight Power dissipation Est. service interval Est. lifetime	14 cm x 63.5 cm (cylindrical) ≈ 11.5 kgf ≈ 1/2 watt > 1 yr > 40 yrs
Operating Characteristics	Range (length change) Linear slew rate Time to complete 50 nm move Absolute repositioning accuracy Relative positioning accuracy	≥ 1.1 mm ≥ 10 µm/sec ≤ 20 ms ≈ 3.8 µm (RMS) < 7 nm (RMS)

Dynamically, the actuator's slew rate requirement is determined by how fast the telescope can change elevation angle during pointing. Temperature changes will augment such gravitational changes, but the rate of temperature change will be relatively slow, and the effect will be relatively small.

Based on our experience with a prototype mirror and actuator set, a typical move request will be a small number of nanometers, less than fourteen. The actuator is mechanically capable of completing a 50 nm move in 20 ms.

Being able to set an actuator to within about 3.8 μm absolute will allow us to restore the mirror to some previously-known condition where all the sensors are within their operating regions. From this condition, the control loop can rapidly converge the system to a desired configuration. The mineral oil in the actuator hydraulics expands significantly but, predictably with temperature, and a talk-lookup correction is necessary to achieve this reproducibility.

4. ACTUATOR TESTS

During production and checkout, each actuator underwent extensive testing. Following simple functional tests to check motor positioning ability, motor current values and variability, and the ability to detect the end-stop, the actuator output shaft was directly coupled to one of the telescope's differential capacitive sensors[3] (Fig. 2), thus permitting us to detect actuator end shaft extension or retraction to within a resolution of better than 2 nm. We measured actuator sensitivity two ways; once using the sensor to measure distance extended and again using a mechanical gauge. The results of the mechanical gauge measurement are shown in Fig. 3.

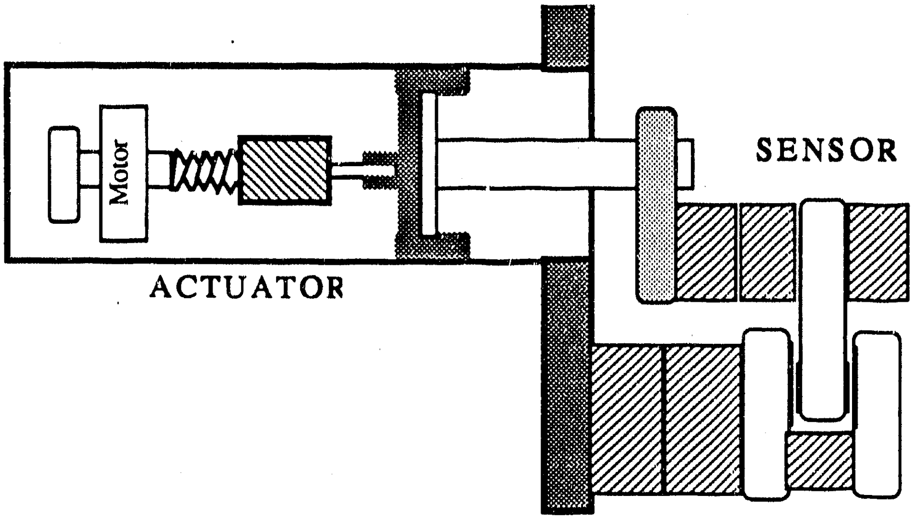

Fig. 2 An actuator with its output shaft directly coupled to the paddle of one of the telescope's displacement sensors. The sensor system measures actuator performance.

To test for range, the actuator is first reset and then run at continuous velocity until it encounters the end-stop at full extension. The stops are detected by monitoring servo motor current. Figures 4 and 5 are by-products of the range test. From Fig. 4, we estimate that a typical actuator will dissipate less than 100 mw during operation at room temperature. Figure 5 shows the range of variations of the motor current for a sample of 100 actuators. High variability flags an actuator as operating in a non-uniform fashion. This is one of our diagnostic tools for predicting failure.

Each actuator undergoes a final set of tests during which 400 moves of random sizes and directions are programmed. The moves are equally split among 5 nm RMS unidirectional moves, 5 nm RMS bi-directional moves, 20 nm RMS unidirectional moves and 20 nm (RMS) bi-directional moves. The time between a move's start and the displacement measurement

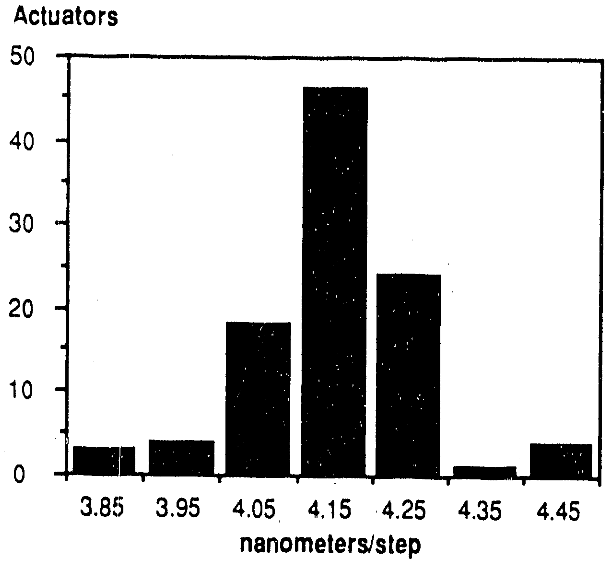

Fig. 3 The distribution of nm/step for a sample of 100 actuators. A caliper gauge press-ing on the end-shaft of the actuator is used to measure extension or retraction during a 100,000 step move.

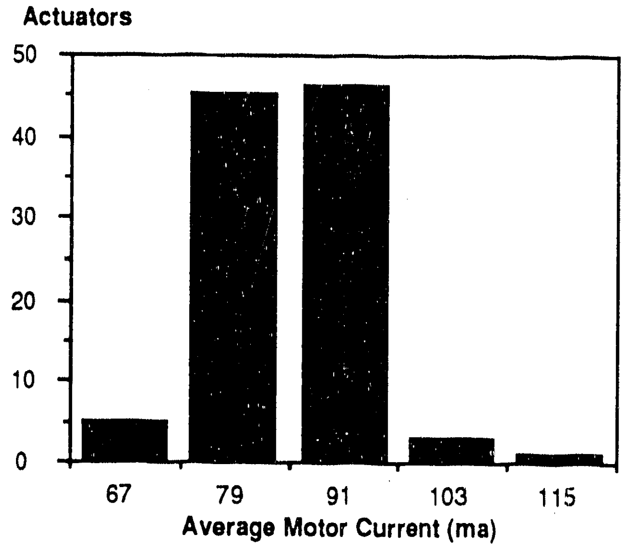

Fig. 4 While testing for actuator range, DC motor current is monitored and averaged. In a sample of 100 actuators, drive current at room temperature averaged about 85 ma, giving a typical actuator motor resistive power dissipation of ~ 87 mw.

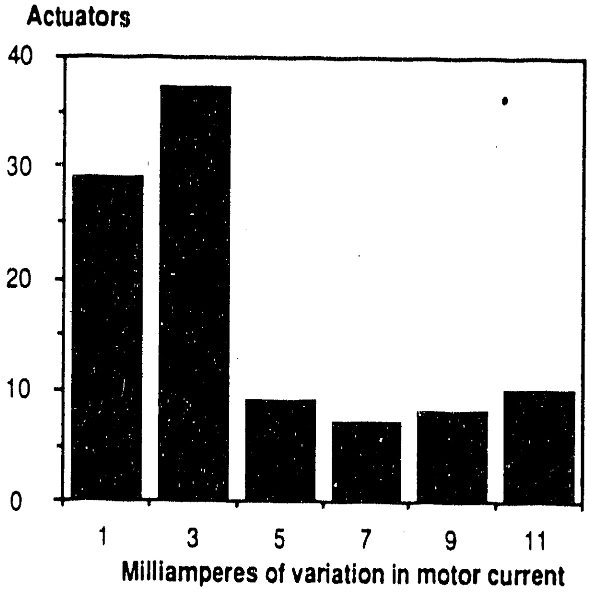

Fig. 5 A histogram of the measured standard deviation of actuator motor current for the long, continuous motion of the range test. By monitoring the variability of motor current during the range test (a long, continuous move), we expect to monitor the general condition of the actuators' bearings, roller screw and ball slide.

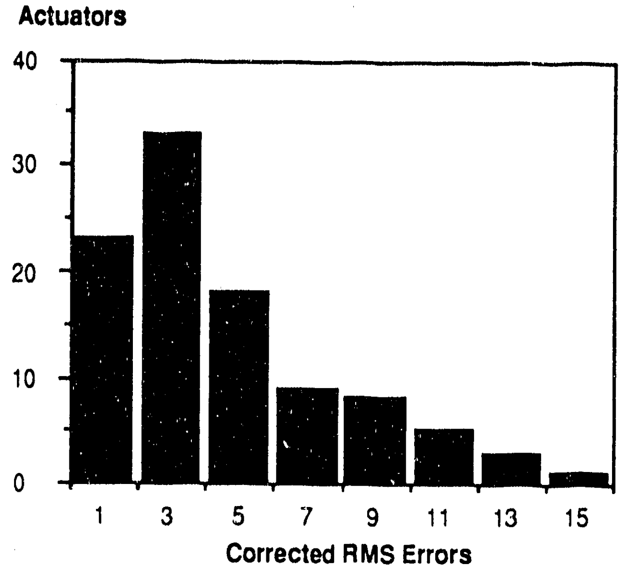

Fig. 6 During testing with an attached sensor, the RMS positioning error of each actuator is determined for a series of 400 random moves designed to mimic expected operating conditions. The maximum of the RMS error, corrected for electronic noise in the sensor system, is histogrammed here. An actuator with RMS errors greater than 20 nm is considered defective.

is 500 ms. The output shaft is monitored via the connected displacement sensor in order to determine the positioning error. The values in Fig. 6 are the maximum of RMS errors detected during the sequence of 400 moves. On the average, actuators will extend or retract to a precision better than 7 nm. A defective actuator will make errors > 20 nm.

5. CONCLUSIONS

Tests of production actuators for the Keck Ten Meter Telescope Primary Mirror indicate the units will easily fulfill their requirements. Positioning errors will average about 5 nm and the power dissipation for all 108 actuators operating simultaneously on the back of the mirror is expected to be less than 50 watts. We are capable of monitoring servo motor current. We are expecting that this will allow us to flag any deterioration of actuator condition although we do not yet have experimental evidence to support this hypothesis.

6. ACKNOWLEDGMENT

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