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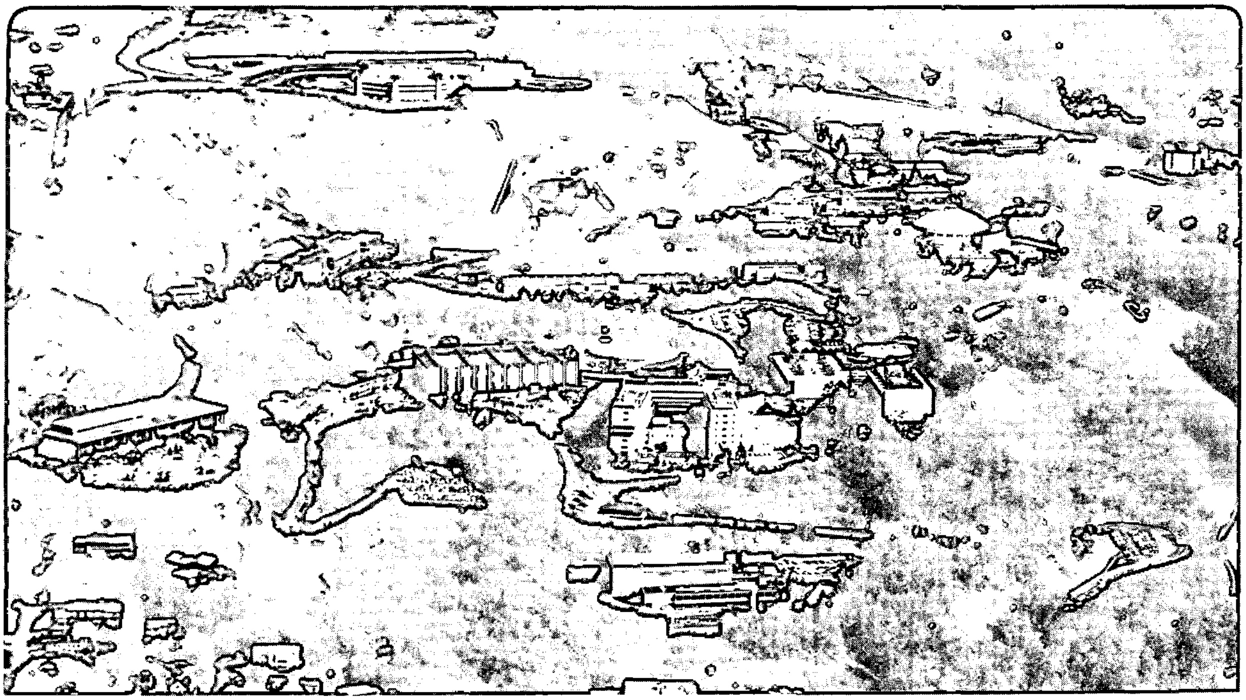

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ABSTRACT

Each of the 108 hydraulic actuators on the Keck ten meter primary mirror lengthens or shortens under electronic control in steps of about four nanometers. The starts and stops of longer moves are profiled to help prevent the stimulation of mirror system mechanical resonances by abrupt actuator length changes. At the move endpoint, the actuator is kept still to prevent the pumping of periodic energy into these resonances. Endpoint stiffness is maintained by electronic feedback. The combined power dissipation of the actuator and its local control system is constrained by the need to minimize heat generation in the vicinity of the mirror. In this paper, we discuss observed stictional and other mechanical phenomena associated with very short bi-directional actuator length changes and trace the impact of the various constraints on actuator controller design and implementation. We present some results of tests with an actuator controller driving an actuator which in turn drives a displacement sensor. The units under test are production devices to be used in the Keck primary mirror active figure control.

1. INTRODUCTION

Keck telescope actuators (Fig. 1) are driven by a dc servomotor/rotary shaft encoder combination which rotates the shaft of a roller screw bi-directionally in increments as small as 1/10,000 of a revolution. The roller screw causes a plunger to be pushed into one end of a hydraulic lever having a mechanical advantage of about 24 : 1. The combination of the 1 mm screw pitch and the hydraulic lever produces about 4 nm of shaft-end movement for each encoder step (1/10,000 of a motor shaft revolution).

Since the end of the plunger is attached to a mirror segment and the body of the actuator is attached to the supporting subcell, plunger movement results in moving the mirror segment with respect to its support. Each mirror segment rests on three of these actuators attached in a triangle on its back side. Consequently, by selectively changing the lengths of three actuators, a mirror segment may be tilted or pistoned in order to correct its position with respect to that of its neighboring mirror segments.

During the conceptual development of the mirror figure control, an abbreviated prototype was built, referred to as the "Technical Demonstration" or, informally, as the "Building 60 Test". The test setup included a large tiltable framework into which was mounted a circular spherical mirror which had been sliced along a chord, and the slice mounted in such a way as to duplicate the edge of what would become an adjacent mirror segment in the final mirror. The large piece of the blank was attached to its support frame by three variable-length actuators, and differential-capacitance sensors were bridged across the gap between the large piece and its severed "ear". The idea was to demonstrate the ability of the sensor, actuator and electronics to maintain the positional relationship across the gap to within the necessary optical tolerances. As far as mirror performance was concerned, the tests succeeded. They also highlighted many remaining problems having to do with, among other things, the actuators and their control electronics, and the peculiarities encountered trying to achieve precise, controlled, small mechanical moves. See Ref. 1 for more information on the Technical Demonstration.

The original actuators[2] used a dc servomotor to rotate a roller screw which drove the output plunger. This differs from the present actuator in that it lacks the intervening hydraulic lever. The present actuator can change length by at least 1.1 mm. It does so in steps of about 4 nm each.

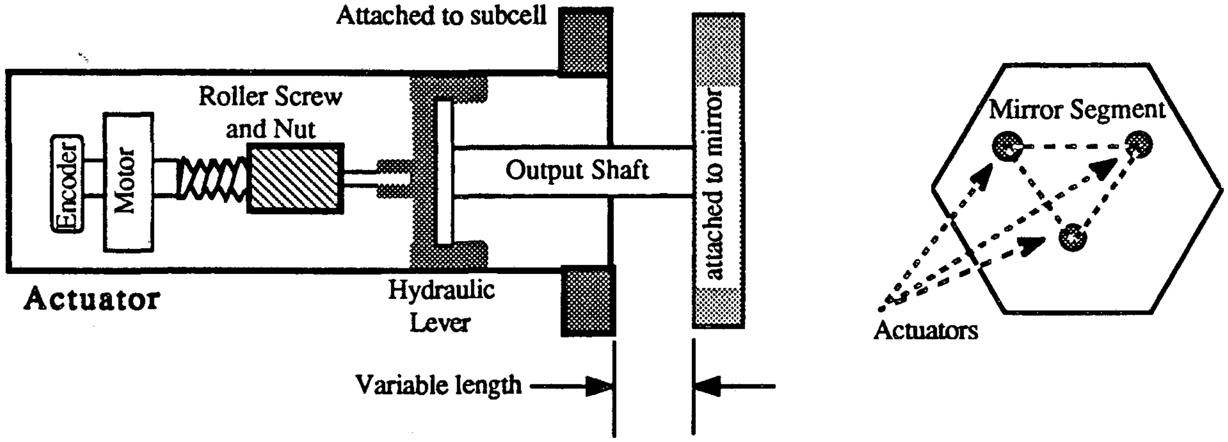

Figure 1: Sketch of a hydraulic actuator for the Keck main mirror and a diagram showing the placement of three actuators on a hexagonal mirror segment. This sketch represents the production version of the actuator. The most significant difference between this and the early prototype actuators is the incorporation of the 24 : 1 hydraulic lever between the roller screw and the output shaft.

As mentioned earlier, each mirror segment rests on three actuators at regular positions of an imaginary triangle in its back side. Since there are 36 mirror segments, each with three actuators, there are 108 actuators in all.

Based on the observed operation of the Technical Demonstration, we expect a typical desired actuator move during operation to be on the order of a few nanometers, only one step of the 10,000-step rotary shaft encoder on each drive motor.

Although a typical actuator length change during operation may be very small, if the telescope is slewing, we expect the mirror support's structural deformation to require changes as large as ten thousand nanometers per second in order to successfully restore good mirror figure within a reasonable time at the end of the operation.

2. CHARACTERISTICS OF SHORT MOVES

There are fundamental differences between what the actuator controller sees at extremes of move distances. Empirically, we notice that very small length changes involve mostly stictional characteristics of the mechanics. Large length changes are, in the main, dominated by rolling friction, with stictional effects at the beginning and at the end. In transition, nonlinearities may exist. We have observed breakaway phenomena, for example and history dependent hysteresis effects.

The controller must maintain stable control throughout both regions and during the transition. Breakaway phenomena, for example, if not controlled, could result in enough overshoot to seriously degrade optical figure integrity.

A short actuator change, say one to ten encoder counts, presents special problems to the controller. These moves tend to be dominated by stiction forces, typically much larger than normal rolling friction. Applying the large force needed to overcome stiction may result in a transition from stiction resistance to the much smaller rolling-friction resistance, and the controller must detect this quickly to avert runaway and the resulting overshoot.

Our observations indicate that within the range of changes of just a few encoder counts, history plays a role in the relationship between the number of rotary shaft encoder tics (measuring angle of shaft rotation) and the distance the output shaft extends or recedes. Similarly, the relationship between servo motor current and shaft encoder outputs is history-related. If the direction of drive is monotonic and then repeatedly monotonic, the output shaft will repeatedly extend or recede the expected 4 nm per encoder tic. There is a large variation in this (we have observed as much as 50%) due to irregularities in the microstructure of the roller screw, but the average is close to the predicted value. The first direction reversal results in much less output shaft movement. If motor shaft rotation is plotted versus output shaft extension, hysteresis is observed, as shown in the right-hand curve in Fig. 2. If an actuator is lengthened by more than about ten 4 nm steps and then shortened,

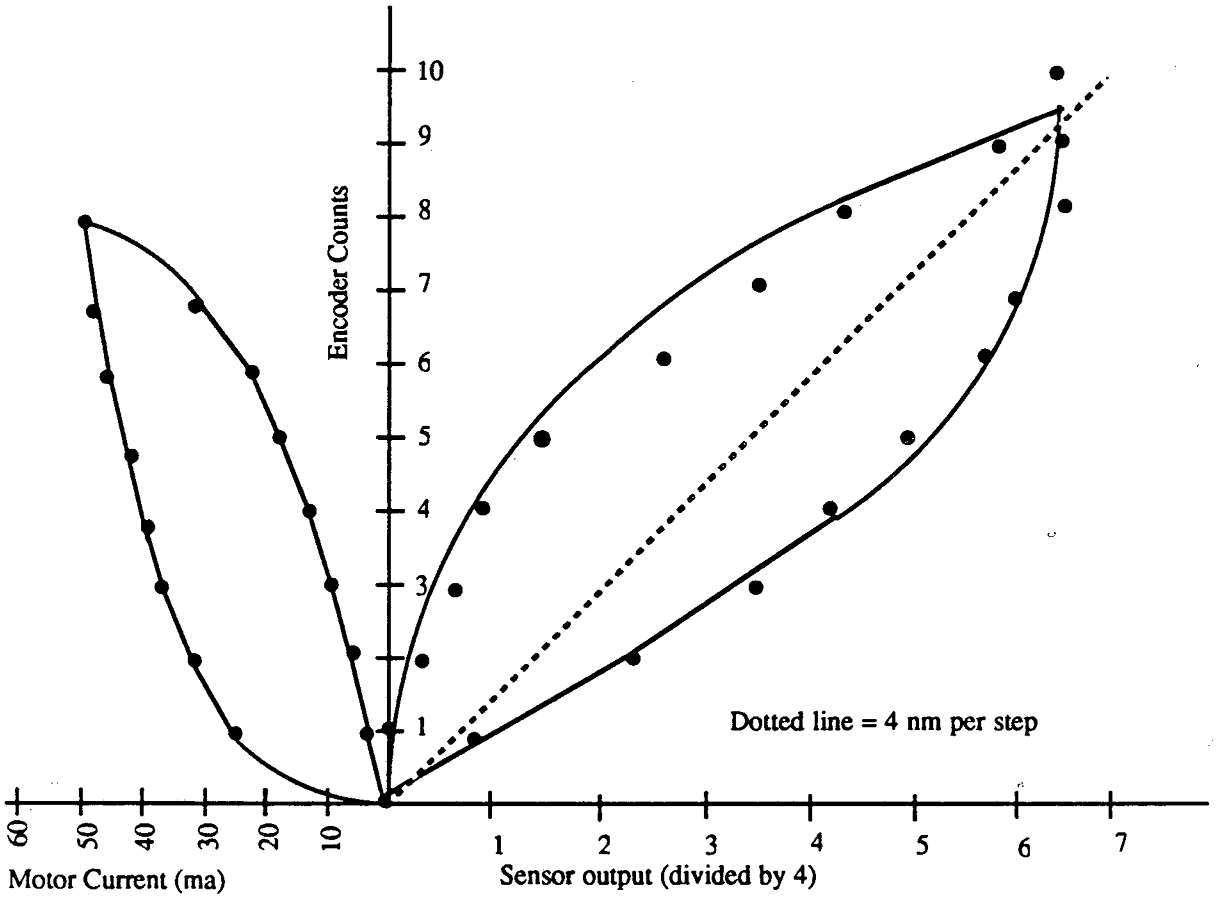

Figure 2: Typical hysteresis in the relationship of actuator servo motor current and motor shaft rotation (left). This characteristic has been observed in all the actuators we have examined. On the right is a plot of motor shaft rotation vs. actuator length. Sizable variations in length change result from microscopic imperfections in the roller screw.

the first few steps after the reversal are shorter than the mechanics would predict. Although in a qualitative sense we know what behavior to expect, the precise relationship is not consistently quantifiable. In a practical sense, the "gain" of the electromechanical actuator assembly is not precisely predictable for very short length changes, if by gain we mean the ratio of rate-of-change of actuator length to servo-motor position, although the sign of the gain ratio is predictable.

3. CONTROLLER OPERATION

The controller's first action is to ramp up motor current an amount linearly proportional to the magnitude of the move request. If the request is small this initial motor current change is very small. Following the input ramp, if the controller detects the actuator has not reached the correct length, it begins to slowly increase motor current. As the shaft moves, the rotary shaft encoder detects the rotation and causes the controller to instantly decrease motor current. The result is a stable, finite motor current at completion. If the shaft encoder detects any change in position from the correct endpoint, the controller once again slowly changes motor current to reverse the errant motion. When the correcting motion is detected, it causes reversal of the motor current change until the correct position is once again achieved.

Mechanically, large changes result in an early break-away from stiction, followed by a region of simple rolling friction and finishing in a monotonic stictional condition as described above for short monotonic changes.

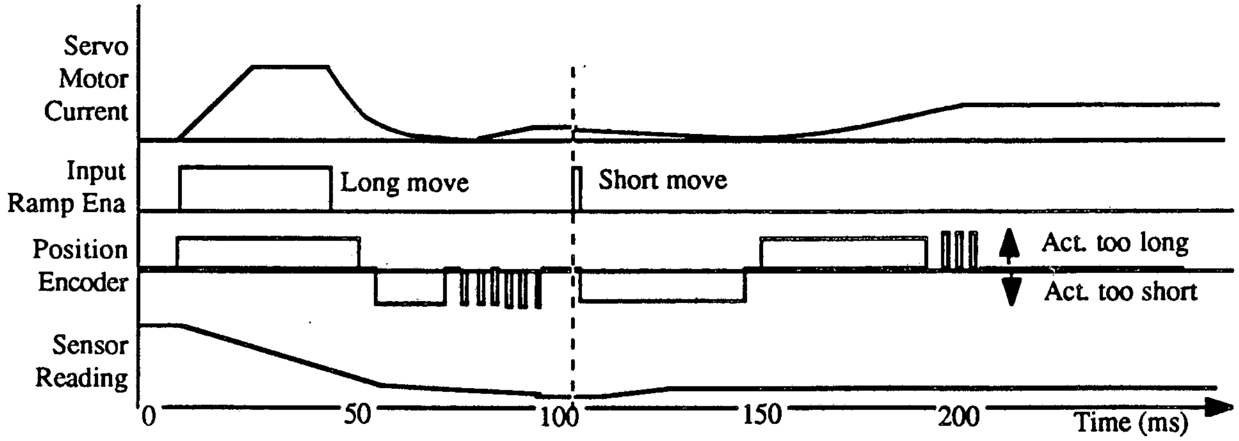

Figure 3: Plot of a long actuator extension (about 500 nm) followed by a shorter one in the reverse direction (about 15 nm). This data is copied from photographs of oscilloscope traces of the actual moves. Both operations take about the same time (110 ms) because the controller slows down near the end. Notice the clipping of the current waveform at the beginning of the first extension. The apparent "hunting" which occurs at the endpoint is due to the "stickiness" of very small motions. Some slow creep will in general occur, and the controller adjusts the holding current until the actuator stops.

As far as the controller is concerned, large length changes work just like small ones with two fundamental differences:

1) There is a preset limit on motor current. While the initial ramp-up of motor current, decreased by the amount of shaft rotation, exceeds a preset value, the ramp-up is stopped. This occurred during the first move in Fig. 3, and resulted in the clipped servo motor current trace.
2) After the initial ramp-up of motor current is complete, the error in position will typically be quite large, and the controller-generated correction attempt will be at a higher rate than that for small changes. As the error gets smaller, the correction rate decreases. The effect is to have moves of any size complete in about the same time.

4. END-POINT STABILIZATION

Because it is highly desirable to minimize heat losses in the vicinity of the mirror, we would like to have the actuators be mechanically stable with the application of little or no motor "holding current". To this end, the hydraulic lever helps the residual magnetism in the servo motor iron and the stiction in the bearings and roller screw assembly to keep the actuator from being driven by its load. Still, some motor current is necessary to completely stabilize the actuator. This may be as high as 40 ma, which translates into about 20 mw/actuator. The actuator controller trims holding current to stabilize the actuator, resulting in the changing position encoder traces at the end of the moves shown in Fig. 3.

The weight of the mirror segment trying to compress the output shaft into the actuator body is the source of the biggest destabilizing force on the actuator. Conversely, the internal actuator spring will, for some telescope altitudes, be the major force on and in the direction of the actuator output shaft. Seismic and wind components may add to these, although to what extent is still not precisely known.

5. ACTUATOR MOVE DYNAMICS

As mentioned earlier, sequential moves all in the same direction encounter stictional resistance over short distances and encounter less-resistive rolling friction if breakaway occurs. Breakaway may result in a small but abrupt change in actuator length during the start of the move, and may result in a small overshoot of the intended endpoint while the controller regains control. As the move winds down, stiction once again becomes dominant, helping to stabilize the mirror after it stops.

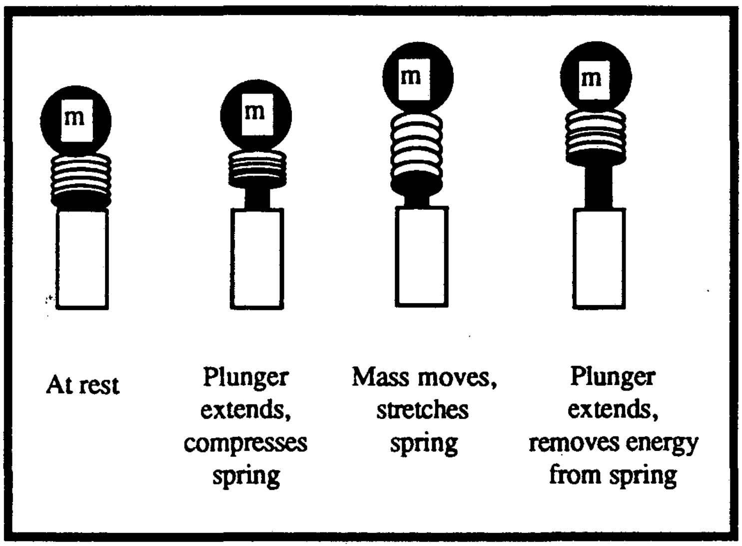

Figure 4: One possibility for adjusting mirror position without pumping energy into the mirror and its support uses the principle of deadbeating, illustrated here. The success of deadbeating depends on the mechanical system being relatively simple and on its being well known. Uncertainties in both respects precluded our use of such a technique.

There is hysteresis in the relationship between motor current change and actuator length change when a direction reversal occurs, as shown in Fig. 2. Immediately after changing direction, the ratio of move distance to motor rotation is smaller than it would be were the move to continue in the same direction.

After several steps without a direction reversal, the relationship between motor voltage and actuator length becomes quantifiably predictable on the average. Based on our experiences with the Technical Demonstration structure, the telescope will be a complex, high-Q, mechanically resonant structure. It will ring for hundreds of milliseconds once stimulated. Consequently, any periodic stimulation may result in the pumping of such resonances resulting in unacceptable levels of structural vibration. The actuator can change length by as little as about 4 nm from a single command. The electro-mechanical inertia of the servo motor prevents rise-times greater than about 2000 nm/s.

One commonly used technique for limiting the amount of energy pumped into a driven mechanical system is known as dead-beating (Fig. 4). If the actuator were thought of as driving a spring (the attachment to the mirror segment) with a mass (the mirror segment) on the other end, the actuator could, by changing length in two equal steps separated by a time equal to 1/4 of the wavelength of the mass/spring resonant period, avoid pumping any excess energy into the system. The first step compresses the spring, thereby storing energy. The spring, 1/4 wavelength later, has stretched by an amount equal to the initial compression, and the mass is at the peak of its excursion and at rest before what would normally be a sinusoidal return. If a second step is now applied to the actuator end of the spring, it compresses the spring to its rest length, removing the restoring force from the mass.

The second step has removed the energy from the spring and left the mass motionless. Dead-beating was attempted on the Technical Demonstration mirror with some success. However, it depends on there being a single, strongly dominant resonance for determining the pulse timing and we were not certain this would be the case in the completed mirror support structure.

6. LIMIT SWITCHING

Closed-loop servo systems with finite resolution experience a phenomenon, called limit switching, which may be ignored in most instances. However, for the telescope, it would prove a disaster. It occurs when the servo loop must find an endpoint, but the resolution of the position detector is finite, preventing the endpoint from being known precisely. Assume, for example, that position is known by counting outputs from a rotary shaft encoder and some specific count is the desired endpoint. The servo loop rotates the shaft until the specific count is obtained, but it has no knowledge of how close the encoder is to generating another count. Any mechanical perturbation may cause a move over the encoder boundary, and the controller, in attempting to correct, will pump energy into some mechanical resonance, resulting in a vibration back and forth across the encoder boundary. Tests on prototype actuators produced measured limit-switching at the rotary shaft encoder of what should have translated into less than a nanometer at the actuator output shaft. In fact, the actuator was changing length by more than a hundred nanometers. In order to eliminate this phenomenon, in the Keck actuator controllers servo loop gain is kept below unity, and we depend on the application of the secondary holding current to achieve final positioning. To achieve this stability, we have sacrificed loop response, but the servo loop's update rate is 500 ms, and consequently, response time is not critical.

7. HEATING

Our budget for heat release near the mirror is 500 W. Based on measurements of the electronics, actuators and cables, we expect the total to be closer to about 250 W. This will be from sources spread out behind the mirror. Each actuator servo motor/shaft encoder combination will dissipate about .5 W. The node boxes, placed one per segment on the platform behind the segments, dissipate about .5 W each, with a measured temperature rise of about 4 °C. Power loss from the power supply cabling distributed throughout the rear mirror area will be less than 9 W. We have taken care to prevent hot spots and to position heat sources as far away from the glass as possible.

The servo control loop around each actuator needs to be minimized in terms of power loss in the electronics as well as power loss in the actuator itself. The electronics must control the actuator as quietly and as gently as possible, not emitting any periodic stimuli to pump energy into structural resonances in the mirror and its support system.

The controller must keep the length of the actuator to within about 20 nm (RMS) of its requested position in order to satisfy optical requirements. It must be able to keep up with the telescope support structure deformation during elevation changes. We estimate the maximum rate of change of actuator length to be 10,000 nm/s.

8. THE LOCAL SERVO LOOP

Limit switching, as mentioned earlier, is not acceptable for the actuator and controller because of the high probability of pumping one or more of the high-Q mechanical resonances in the mirror and its support structure. In order to build a controller which guaranteed accurate endpoint positioning as well as one which did not quiver at the end of a move, we implemented it as a multi-stage controller. Figure 5 is a functional representation of the motor controller. Figure 6 is its logical structure. First, moves are loaded into the controller as digital numbers representing the number of 4 nm steps to take. The sign of the count gives the direction. It is fed, count-by-count at 5 kHz (thus the profile of the motor current rise), into a device which translates each incoming count into a motor voltage step. As the actuator servo motor rotates, its rotary shaft encoder causes counts to be subtracted from the motor voltage control.

If the motor voltage exceeds a preset value, the 5 kHz clocking of the input is stopped until the motor rotates the encoder enough to lower the voltage (Fig. 5, loop 1). When the entire input count is finally unloaded, this input loop switches off. The difference between where the servo motor should be and where it is is continuously monitored as a digital value (Fig. 5, loop 2). When the input is finished, an integrator is enabled which changes the motor voltage in proportion to the time the motor is not positioned properly and in proportion to the extent of the position error (Fig. 5, loop 3). When the output of the integrator stops changing, the servo motor, and concurrently, the actuator, is stable and in position. By making one voltage step from the integrator the equivalent of less than one step of motion of the rotary shaft encoder, the effective loop gain is less than one, and there is no limit switching.

As the move approaches its endpoint, as given by the value of the difference as described above, the clock which causes the integrator to accumulate is slowed. This results in the tailing off of motor current change rate. At the start of a move, the clock rate remains fixed, and motor voltage is linearly ramped until shaft encoder returns start bending over the top of the ramp and/or the maximum voltage is reached and the ramp is clipped. Figure 3 contains sketches of two moves of different lengths.

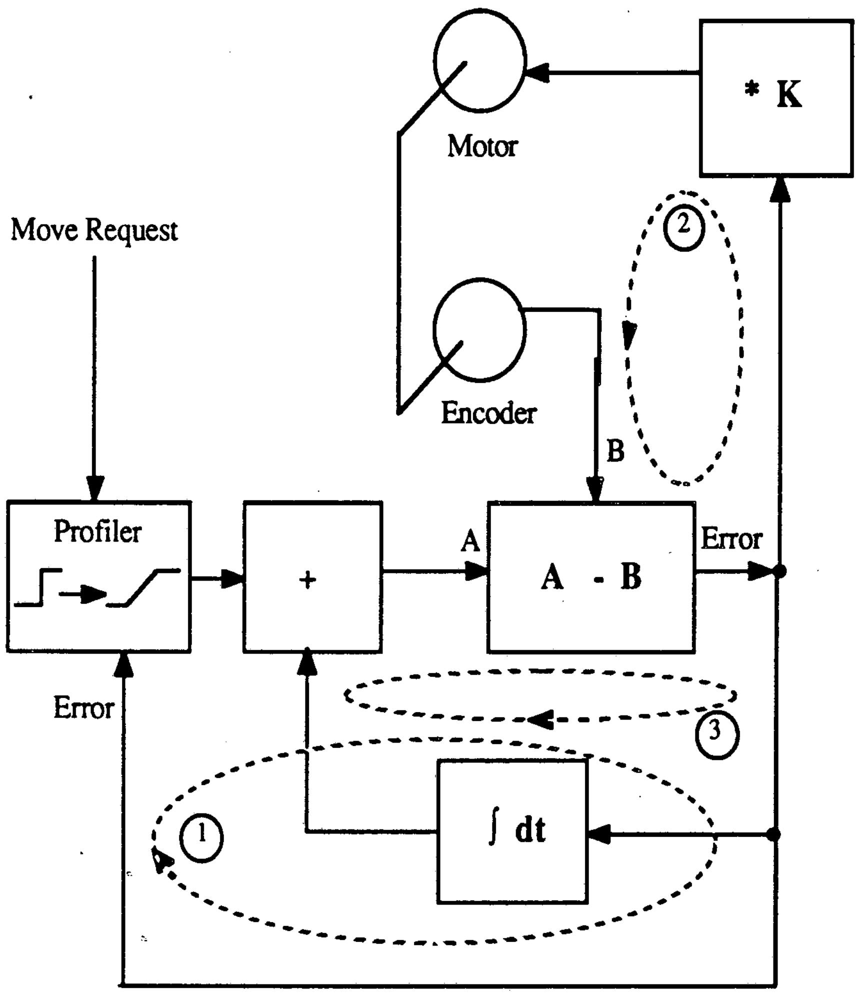

Figure 5: The actuator servo loop showing the three functional loops. The input loop at the left generates a motor voltage ramp which may be clipped if the error term exceeds a predetermined value (1). The stiffness loop (2) continuously monitors motor position and develops an error voltage which tends to reduce the error. The integrator (3) monitors position error and time-integrates it to augment the stiffness loop, insuring accurate positioning.

After the move has once reached its endpoint, the integrator is left enabled, so anything which results in an actuator position change as seen by the shaft encoder will result in corrective action by the controller.

Actuator heating results from three factors. One is the holding current passing through the resistive component of the servo motor windings. This amounts to about 20 mW/actuator, The second source of heating in the actuator is the electronics in the rotary shaft encoder, dominated by the loss in a light-emitting diode used as part of the position sensing. This amounts to about 450 mW. Finally, the actuator contains electronics to sense when it is in home position, forming a reference position to be used as absolute position zero. This assembly dissipates about 50 mW. The actuator controller dissipates about 1560 mW for three actuators, or 520 mW/actuator.

The actuator controller card plugs into the mirror segment's Node Box, and one card controls three actuators. The actuator servo motor, rotary shaft encoder and home position sensor all are at the end of the actuator farthest from the mirror. The Node Box is mounted in the mirror segment's subcell about 2 meters from the back surface of the mirror glass, and is built out of aluminum to help in spreading and radiating heat.

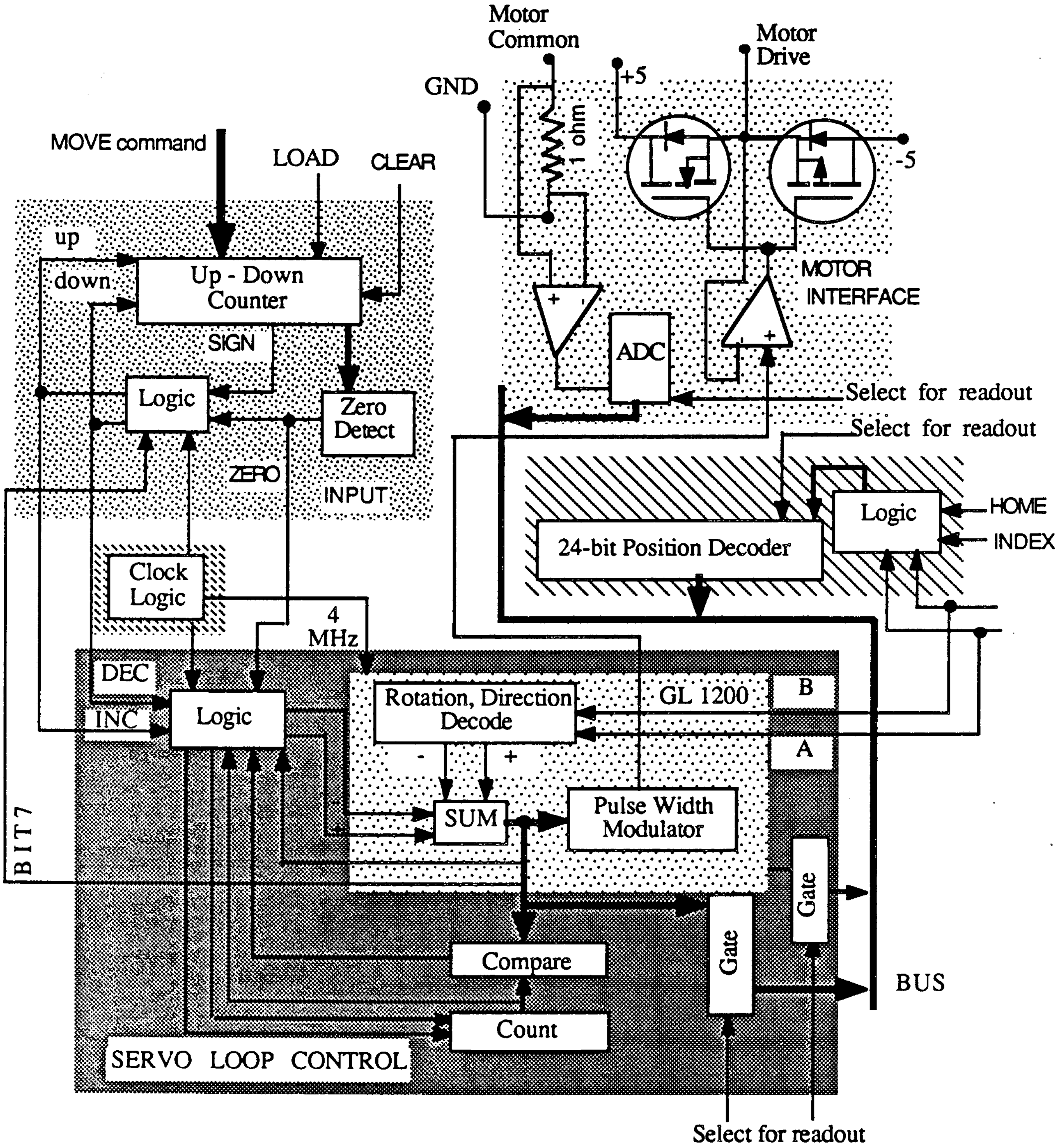

Figure 6: Block diagram showing the logic of the actuator controller. The major components are the input section, the servo loop control section, the motor interface and a position decoder whose contents are the Absolute Position of the actuator. Most of the logic boxes are implemented in EPLD devices. The GL 1200 is a CMOS motor-control chip produced by GALIL. Each actuator controller printed circuit board contains three sets of this logic plus a few devices to handle the common readout bus.

9. CONCLUSIONS

The Keck primary mirror figure control actuators and their controllers meet our design objectives of low power, quiet move-end operation and accurate positioning, verified by measurements of production devices. We have made every effort to minimize and to spread what heat there is over a large surface area and to keep it removed from the mirror glass. The actuator controller performs very small length changes satisfactorily even though there is hysteresis in the relationship between motor current and motor shaft rotation and in the relationship between motor shaft rotation and actuator output shaft extension. Simple schemes for preventing pumping of structural resonances, such as dead beating, were considered but the predicted complexity of the mirrors and their support structure prevented accurately predicting their success or failure, and they were laid aside.

10. ACKNOWLEDGMENTS

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