Segmented Mirror Control System Hardware for CELT

Terry S. Mast and Jerry E. Nelson
University of California Observatories / Lick Observatory
University of California, Santa Cruz
1156 High Street, Santa Cruz, CA 95064
mast@ucolick.org

ABSTRACT

The primary mirror of the proposed California Extremely Large Telescope (CELT) is a 30-meter diameter mosaic of hexagonal segments. The primary mirror active control will be achieved using four systems: sensors, actuators, processor, and alignment camera. We describe here the basic requirements of sensors and actuators, sketch a sensor design, and indicate interesting actuator alternatives.

Keywords: sensors, actuators, segmented mirror, large optics, CELT

1. CELT OVERVIEW

We are designing a 30-meter-diameter telescope for astronomy at visible and infrared wavelengths. The project is a collaboration of the University of California and the California Institute of Technology, and the telescope is currently named the California Extremely Large Telescope (CELT). The project overview is given in another paper at this conference (Design Concepts for the California Extremely Large Telescope (CELT), Nelson, 2000) and in a series of internal project reports.

The telescope optical design calls for Ritchey-Chretien foci with the following parameters. For comparison we also list design parameters for the W. M. Keck telescopes.

	CELT	**Keck**
primary diameter (m)	30	10
primary focal ratio	1.50	1.75
backfocal distance (m)	15.00	2.5
primary radiius of curvature (m)	90.000	35.000
primary conic constant	–1.0028	–1.003683
secondary radius of curvature (m)	–12.12	–4.738
secondary conic constant	–1.525	–1.644
final focal length (m)	450	150

The focal ratio of the primary (1.50) was chosen as a compromise between minimizing the segment asphericity (minimizing the segment fabrication costs) and minimizing the size of the dome (a significant fraction of the observatory cost).

The large primary mirror will be segmented and the piston/tip/tilt degrees of freedom of each segment will be under active control. The segmentation geometry is discussed below. Other papers at this conference discuss the fabrication of segments (Primary Mirror Segment Fabrication for CELT, Mast and Nelson, 2000) and the control system design (Design Issues for the Active Control System of the California Extremely Large Telescope (CELT), Chanan *etal.*, 2000b).

The increase in primary mirror diameter from 10 meters to 30 meters is a challenging advance. In order to begin construction in two to three years, we believe that major innovations in technology will not be possible. The emphasis of the development and innovation for this project will be directed toward reducing costs of largely existing technologies.

Segment Design

The selection of a segment size, and hence the number of segments, depends on a complex tradeoff of many costs. A larger segment size (radius = a, thickness = h) increases the amount of asphericity required in the surface figure ($\sim a^2$), the gravity-induced deflections on a support ($\sim a^4 / h^2$) , the weight for handling ($\sim a^2$ h), and the sensitivity to position errors in the array ($\sim a^2$). A smaller segment size increases the number of active control actuators and sensors, the complexity of a control wavefront sensor, and the complexity of the alignment and control software.

The selection of the segment thickness is also a complex compromise between costs. A larger thickness will require larger required forces for intentional deformation during fabrication, greater cost of the blank material, greater thermal inertia in the telescope, and a greater mass for the support structure (the telescope). A smaller thickness will require more support points to reduce deformations due to gravity.

At this early phase of the design we have not yet gathered estimates of these costs and cost variations. This will be required to make final informed compromises. Based on our experience with the Keck telescopes, we have adopted for now a baseline segment design. During the coming phases this will evolve to final values for the radius and thickness. In the meantime we have adopted a segment radius of a = 0.5 meters and a segment thickness of h = 45 millimeters.

The resulting array (Figure 1) contains 1080 segments. A central subset of 19 segments is deleted from the array since the light to them is blocked by the secondary mirror.

We have the option of adjusting the positions of some peripheral segments to keep a closely circular periphery and at the same time to allow for convenient division of the array into subsets (full and partial “rafts” of 19 segments) for ease of handling. The array shown in Figure 1 has an area = 702 m^2.

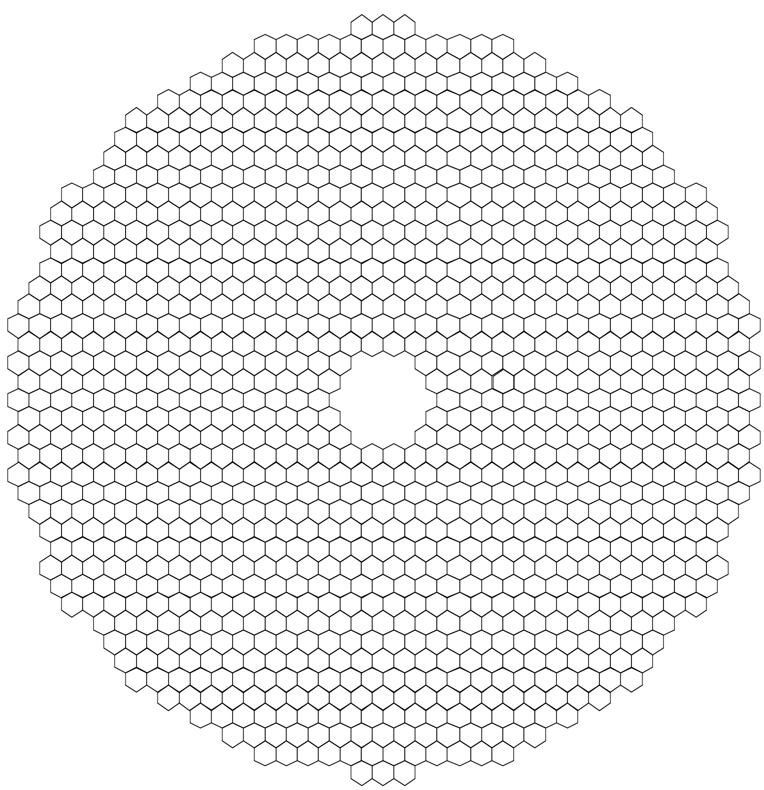

Figure 1. Segmentation option for the CELT primary mirror containing 1080 segments.

2. SEGMENTED ACTIVE CONTROL OVERVIEW

Properly supported, CELT segments can be treated as rigid objects. Their position can be described by six parameters. Three of these (in-surface motions) can be adequately controlled passively. The other three (piston, tip, tilt) will be actively controlled by three actuators attached to the telescope mirror cell.

Perturbations Requiring Correction

There are both thermally-induced and gravitationally-induced changes in the axial positions of the segment supports. The control system moves the actuators to correct for these support changes. These changes are large enough to clearly require active control, yet they change sufficiently slowly that a relatively low system bandwidth is adequate.

As the elevation angle of the telescope changes, the changing direction of gravity deforms the mirror cell. In moving from horizon to zenith the deformation is dominated by a parabolic sagging of the cell. We expect the outer segment supports will move in piston about 1 mm relative to those of the inner segments. Thus the rms surface error will change by about 600 microns in going from zenith to horizon. The maximum rate of piston change is about 40 nm / second. The segments will tilt, and without active control, the rms image radius would grow to about 100 arc seconds in diameter.

As the temperature of the steel support structure changes, the mirror support positions also change. Over an expected operating range of about 10^{o}C and without active control, the relative segment heights change by about 10 microns. In addition, temperature variations within the structure of 1^{o}C will produce comparable distortions.

Control Hardware

Four hardware systems are required for the active control.

- Sensors

  We will use both displacement sensors on the edges of the segments and a Hartmann-Shack wavefront sensor observing a star. The information from both subsystems will be combined and used simultaneously in the control algorithm.
- Actuators (three per segment)
- Processor

  The processor calculates the control matrix from the system geometry and then for each control cycle performs the matrix multiplication required to calculate the desired actuator motions.
- Alignment Camera

  Using star light this instrument establishes the desired sensor readings. These desired sensor readings result in segment piston/tip/tilt degrees of freedom that geometrically stack the images from the segments and accurately phase the segment surfaces.

All four systems must be designed in concert since the requirements for each depends strongly on the others. Our work to date has addressed primarily the displacement sensors (Section 3) and actuators (Section 4). The alignment camera is critical to the success of the system, and since it is a complex optical instrument we will address its design in the coming year. The wavefront sensor subsystem is also potentially complex, however, it is less specific to CELT, and its detailed design can be delayed. Although the control matricies are large (potentially ~ 3300 by ~ 8500), the processor performance requirements will probably not require CELT-specific technology development. We will delay the design and specification of the processor hardware to a later phase of the design program.

The number of sensors and actuators for Keck and CELT are as follows.

	Keck	**CELT**
Number of inter-segment edges	84	3102
Number of displacement sensors	168	6204
Number of actuators	108	3240

The number of actuators and displacement sensors for CELT are about thirty times those required for Keck. Each displacement sensor for Keck cost roughly $5000 each and each actuator roughly $7000 each. Given the large quantities, it is imperative to dramatically reduce the costs of these elements.

Control Algorithm

The piston, tip, and tilt of each segment will be adjusted by three actuators located at the vertices of an equilateral triangle. The control algorithm calculates a set of actuator moves in response to a set of sensor readings.

The relative orientations of the segments are measured by two sensor subsystems; displacement sensors and a wavefront sensor. Each displacement sensor measures locally the relative height of two adjacent segments. There will be two sensors along each inter-segment edge for a total 6204 displacement sensors. The wavefront sensor subsystem uses a star to generate x,y centroid coordinates from each subaperture. We have not yet defined the number of subapertures, but the minimum will measure focus, tip, and tilt of the array. The full vector of sensor readings contains two parts; displacement-sensor displacements and wavefront-sensor centroids.

There are many more sensor readings than actuators, and thus the system is highly over determined. The full sensor vector will be used in a chi-square fit to determine the best-estimate of the piston, tip, and tilt of each segment. Based on these, commands will be sent to the actuators to drive the sensor readings to externally-determined *desired sensor readings.* This read-and-correct cycle will be repeated approximately ten times per second (Keck actuators are updated two times per second, Jared, *etal*.,1990, and Cohen, *etal*., 1990)

The vector of sensor reading changes, $\delta\mathbf{s}$, that results from a vector of actuator motions, $\delta\mathbf{p}$, is defined by a matrix $\mathbf{A}$.

$$\delta\mathbf{s} = \mathbf{A}\,\delta\mathbf{p}$$

The elements of **A** will be calculated from the geometry of the segments, the locations of the actuators and displacement sensors, and the mapping of the wavefront-sensor apertures to the primary mirror.

The control requires solving an over determined set of equations. The result of a linear chisquare fit is a pseudo-inverse matrix **B**. The matrix **B** depends only on the matrix **A,** and given the system geometry, it will be calculated and stored. For each control cycle, the optimum actuator motions, $\delta\mathbf{p}^*$, are calculated using **B**

$$\delta\mathbf{p}^* = \mathbf{B}\,(\mathbf{s} - \mathbf{s_d})$$ where $\mathbf{s_d}$ is the vector of desired sensor readings, and

$$\delta\mathbf{p}_{\text{applied}} = g\,\delta\mathbf{p}^*$$ where g is the control system gain, and $\delta\mathbf{p}_{\text{applied}}$ is the command vector sent to the actuators.

The desired sensor readings ($\mathbf{s_d}$) are determined by measuring optically the positions of the individual segment images in the focal plane and the piston errors in the surface of the array. These measurements will be made using the alignment camera. This instrument for the CELT active control system has not been designed; it will be similar to that used for Keck (Chanan *etal*., 1988, 1994a,b, 1998, 1999, 2000a). The vector $\mathbf{s_d}$ is the vector of sensor readings that results as closely as possible in 1) all segment images being coalesced and 2) all relative piston errors being zeroed.

Focus Mode

The displacement sensors measure the relative piston, tip, and tilt of the segments. They do not measure the overall piston, tip, tilt of the primary mirror. Thus there are $3N_{segments} - 3$ degrees of freedom measured. In addtion, however, there is a single additional degree of freedom (or mode) that is not measured by the CELT displacement sensors. In this “focus” mode the same dihedral angle appears at all of the inter-segment edges. This is effectively a change in the radius of curvature or focal length of the array. Since this mode does not have relative segment height displacements, it is undetected by displacement sensors. For Keck this mode is measurable due to the offset of the sensor from the segment edge. For CELT this offset is zero, and this mode will be measured by the wavefront sensor.

Noise Propagation

CELT will be used both with and without adaptive optics, and we will develop error budgets for both modes. In this paper we make some rough estimates to initially define the sensor noise and actuator noise requirements.

Without Adaptive Optics

We will define the budget in terms of rms slope errors or, equivalently, geometric image size. Based on the results from Nelson, *etal.* (1985) and Chanan, *etal.* (2000), we expect the rms image radius, θ_{rms} , to be given by

$$\theta_{rms}^2 = (\gamma\, \sigma_{sensor} / a)^2 + (\delta\, \sigma_{actuator} / a)^2$$

where a = the segment radius

If we exclude the focus mode,

the coefficients for Keck are $\gamma = 3.88$, $\delta = 4.4$.

Initial estimates for CELT give roughly $\gamma = 5$, $\delta = 4.4$.

If we budget $\theta_{rms} = 0.014$ arc seconds each to actuators and sensors, then we need

$\sigma_{sensor} < 7$ nm and $\sigma_{actuator} < 7.5$ nm.

With Adaptive Optics

Both displacement sensor noise and actuator noise, σ_{sensor} and $\sigma_{actuator}$, will contribute to surface errors in the primary. The rms surface error and the resulting image blur were studied for the Keck design (Nelson, *etal*., 1985 and Chanan *etal*., 2000), and this has been extended to the CELT design. We consider first the rms surface errors when uncorrected by adaptive optics. The rms surface error is given by

$$(S_{rms})^2 = (\alpha\, \sigma_{sensor})^2 + (\beta\, \sigma_{actuator})^2$$

for Keck $\alpha = 4.2$ and $\beta = 1.06$

for CELT $\alpha = 16$ and $\beta = 1.06$ (focus mode excluded)

Sensor noise induces primary mirror surface errors that are dominated by low spatial frequencies; hence, the mirror is very smooth with edge discontinuities $< \sigma_{sensor}$.

We will define the budget in terms of the residual (after adaptive-optics correction) rms wavefront errors. We will work to ensure that the residual errors from the primary mirror are smaller than the residual errors from the atmosphere.

We next ask how these scale with the number of terms corrected. For a Shack-Hartmann wavefront sensor, the residual atmospheric wavefront error after correcting N terms scales as $N^{-0.43}$ (Noll, 1976). The residual error in the actively-controlled primary residual scales roughly as $N^{-0.6}$ (Chanan, *etal.*, 2000b). Thus, for large N we expect the residual errors will be dominated by the atmosphere as desired.

Assuming a Kolmogorov atmosphere with r_0 = 0.2 meters at λ = 500 nm , a 30-meter diameter telescope, and adaptive optics correction of the first 5000 terms; yields a residual rms wavefront of ~ 70 nm (Noll, 1976).

The relationship between this residual rms wavefront and sensor noise for the actively-controlled primary can be roughly estimated using the mode decomposition of Chanan (2000b). If the lowest 200 modes of the segmented-array are corrected by the adaptive optics system, then the ratio, (rms wavefront) / (sensor noise), is close to unity. For a larger number of corrected modes this ratio falls to less than unity. This suggests that for observations with adaptive optics the sensor noise can be ~ 70 nm.

We conclude that the CELT sensor noise requirement is constrained by the observations without adaptive optics.

Based on the above considerations we select as reasonable initial noise goals:

$\sigma_{sensor} < 7$ nm and $\sigma_{actuator} < 7$ nm.

Error Budget

The telescope error budget (Nelson, 2000); and within that, the error budget for the primary mirror, contains terms budgeted to the active control system. The error budget has not been developed yet in detail. The sources of wavefront degradation are listed below along with preliminary estimates for their contributions. These preliminary values are defined largely by the requirements for adaptive optics. Some fraction of the time the telescope will be used without adaptive optics, and then the following error budget will provide an image quality that does not degrade that induced by the atmosphere.

Active Control System Contributions to the Wavefront Error Budget.

	Budgeted Wavefront Error (nanometers rms)	
Control system noise		30
Sensor noise	28	
Actuator noise	10	
Thermal effects on sensors		10
Gravity effects on sensors		10
Vibration		25
Star stacking errors		10
Phasing errors		25
Total		50

The ratios of the terms here is roughly that used for the Keck telescopes (Mast and Nelson, 1986). We assume that adaptive optics has removed the low order wavefront errors introduced in the primary by the active control system.

3. DISPLACEMENT SENSORS

Displacement Sensor Requirements

The requirements for the CELT sensors are very similar to those achieved for the Keck telescopes. The table below is a initial estimate of the requirements (Jackson and Shimizu, 1987, and Mast, 1983).

	CELT	**Keck**
Noise referred to input	< 7 nm	< 6 nm
Displacement range	± 200 µm	± 12 µm
Balance adjustment	± 500 µm	± 80 µm
Sensor sensitivity	~ 0.4 mV/nm	~ 0.4 mV / nm
Frequency response	dc to 80 Hz (-6 db)	dc to 80 Hz (-6 db)
ADC range	16 bits plus sign	12 bits plus sign
ADC sensitivity	~ 3 nm/ count	~ 2.9 nm / count
System stability	< 3nm / week	< 3nm / week
Temperature coefficient	< 3 nm / ^{o}C	< 3 nm / ^{o}C
Operating temperature	2 ± 8 ^{o}C	2 ± 8 ^{o}C

Keck Displacement Sensor - Mechanical Design

The mechanical design of the Keck sensors (Mast and Cohen, 1988, and Minor *etal.*, 1990) is complex and expensive. A plan view of the assemblies is shown in Figure 2. Each sensor consists of seven polished Zerodur plates (3 Drive and 4 Sense) that are spring-loaded together and spring loaded to the back of the segments. The attachment to the segment required drilling holes in the back of the segment and bonding inserts into them. The two assemblies (Drive and Sense) are on adjacent segments and interlock across the segment gap. Thus, to physically remove a segment from the array, the Drive plate must be manually released and rotated out from between the Sense plates. Tight tolerances on the angle of the Drive plate required the fabrication of a segment-specific mounting surface on the Drive assembly.

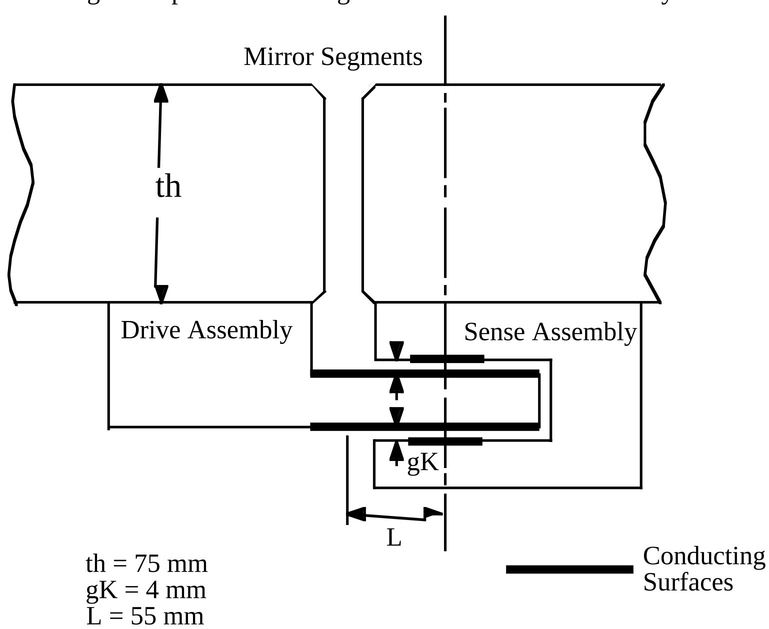

Figure 2. Schematic drawing of the Keck displacement sensor. The reflecting surfaces of the 75-mm-thick segments are at the top of the figure.

Regions of the sensor surfaces are metal coated to provide two capacitors (gap = gK). The capacitance difference is sensitive to vertical relative segment displacement. The coating is a 2.5-micron layer of gold on a 0.5-micron layer of chrome. The sensing capacitors are offset from the segment gap plane by the distance L, and this offset provides of measure of focus mode.

Keck Displacement Sensor - Electronics

Figure 3 is a sketch illustrating the functions of the Keck displacement-sensor electronics (Mast and Cohen, 1988). A drive voltage, V_{drive}, is alternately switched between the two capacitors. The sum of the charges on the capacitors is amplified, rectified, integrated, and digitized. A displacement δz induces an output

$$d Q = V_{drive}\, \varepsilon\, 2\, dz\, h^2 / g_K ,$$

where the capacitor dimensions are h x h (h = 30 mm), the capacitor gap g_K = 4 mm, and ε is the dielectric constant . An offset voltage is added to one side of the drive voltage to account for a physical offset and provide an the output close to Q = 0. A physical offset results from fabrication and assembly variations of the sensor position with respect to the front surface.

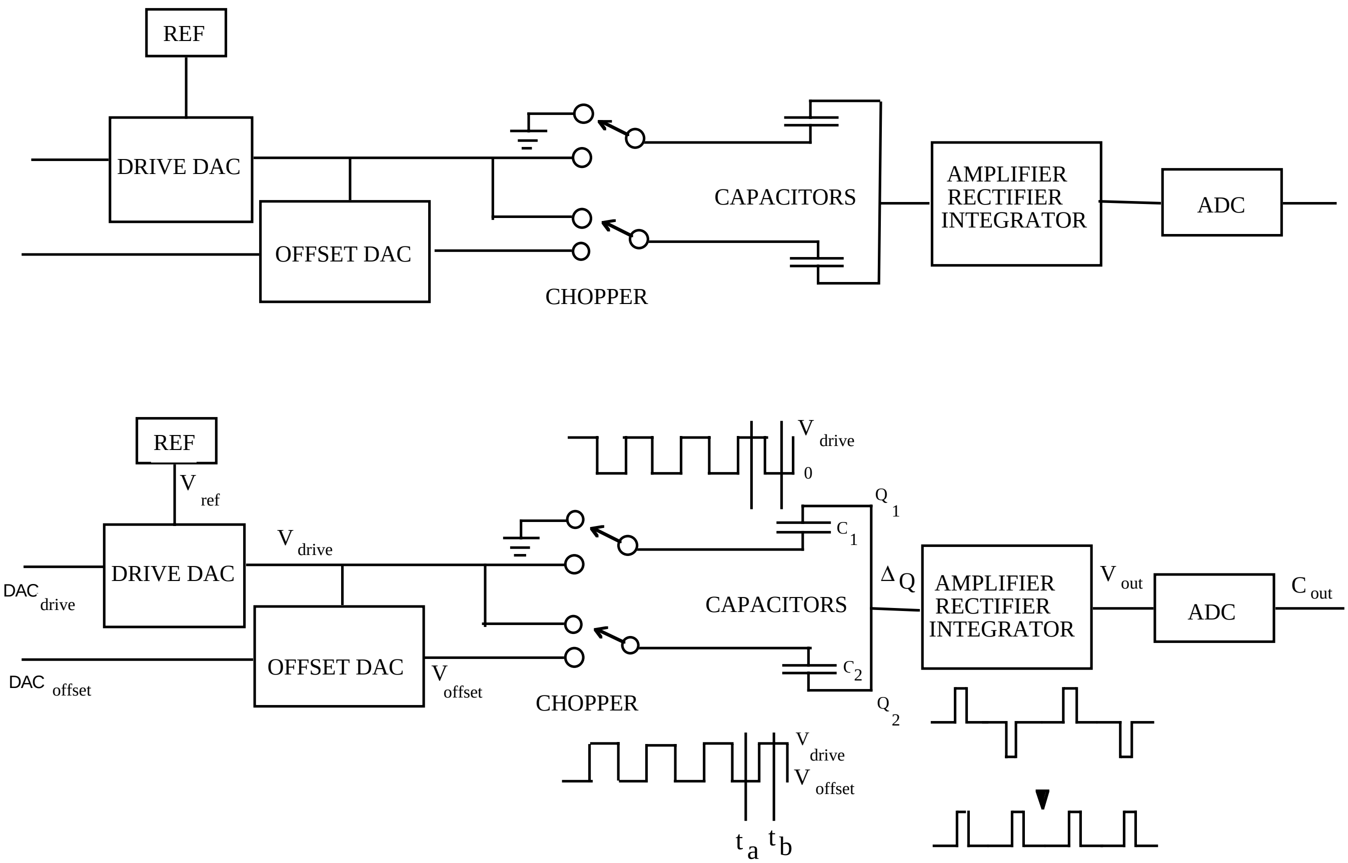

Figure 3. Schematic of the Keck sensor electronics functions.

CELT Displacement Sensor - Mechanical

For CELT we propose a mechanical sensor design that will be substantially less expensive than that used for Keck. The sensor capacitors will be bonded to the surfaces of the segments inside the inter-segment gaps (Figure 4). For a baseline design we assume the mechanical sensor is a printed circuit in a Kapton substrate that is bonded to the edge surface. The printed circuit will contain the required capacitors, leads, and ground planes. It will wrap below and onto the back of the segment where a pre-amplifier and cable connectors for the drive and sense electronics will be attached. The total thickness of the circuit and bonding agent within the gap can be less than 0.2 mm, a small fraction of the proposed 2 mm gap between segments.

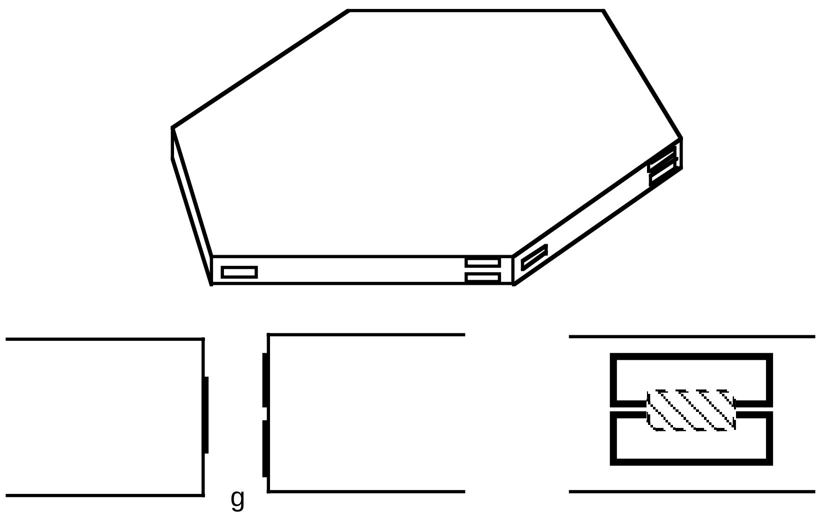

Figure 4

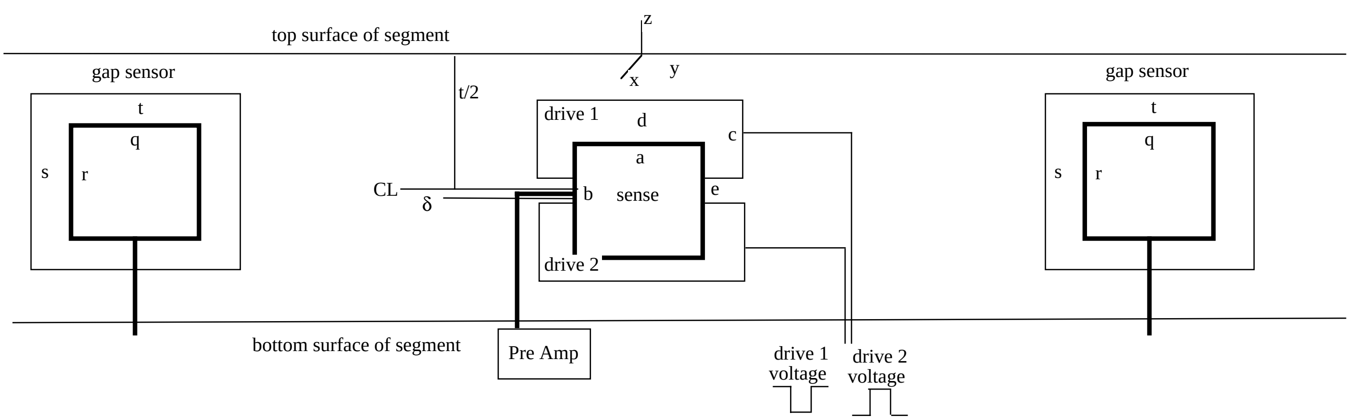

Figure 5

Figure 5 shows a preliminary layout of the sensing and drive capacitors. We have called out some of the dimensions to be determined. The capacitor plates r,q and a,b are on one segment, and s,t and d,c are on the segment across the gap (g). The basic signal that measures the vertical (z) displacement (δz) of one segment with respect to its neighbor is generated by the difference in capacitance of the sense capacitor with respect to the drive_1 and drive_2 capacitors. A displacement δz induces an output

$$dQ = V_{drive}\, \varepsilon\, 2\, \delta z\, a / g$$

In addition to being sensitive to this vertical displacement, the drive/sense capacitances are also sensitive to a change in the gap size (as well as the dielectric constant of the air). Changes in the gap size will be induced by deformation of the telescope mirror cell as the telescope changes elevation angle and by changes in the temperature of the steel cell.

If the steel cell changes temperature by 10^{o}C, then the gaps between segments will change by about 100 microns, or 5% of the total gap. If the sensor were operating around the physical null, then this creates a small fractional error in the sensor reading and only slightly increases the control cycles required to iterate to the desired null. However, in practice large offsets are required, of order 200 microns; and a 5% error in this large offset greatly exceeds the allowed errors.

To reduce the sensitivity of the sensor to gap changes we will adjust (as with Keck) the drive voltage difference until the electrical output is near null, when the segment height difference is zero. As a result, gap changes will still affect the sensor sensitivity, but will not shift the location of the null.

The gravity-induced deformation of the cell also causes differential motions between segments and changes the gaps. In the Keck telescopes this causes the center positions of the segments to move radially up to 0.37 mm and rotate about the segment center up to 0.00025 radians (Mast, 1987). This would induce changes that are a large fraction of the 2 mm gap. An important goal of the CELT mirror cell design will be to keep the gravity-induced gap changes to less than 100 microns.

To reduce that adverse consequences of these two effects we will make independent measurements of the gap using a pair of gap sensors (Figure 5). The gap sensors are equally distant from the sense capacitor to distinguish between a change in the average gap thickness and a wedge change in the gap. The “gap” capacitor geometry is chosen to make the signals insensitive to small transverse motions. The signals from the two gap capacitors can be added directly, and thus only one additional read circuit is required.

With Keck the sensor gains are known to 0.1%. This is useful for various calibration tasks and this is a goal for CELT.

In principle, the drive voltages will originate from one segment, and the sense signal can be read on the other segment. However, this will result in a large ground loop that will be sensitive to noise pickup. To minimize this sensitivity we prefer to have both the drive and sense electronics on the same side of the gap. This could be achieved by coupling a small cable across the gap to carry the drive voltages or sense signal as is done for Keck. However, this would require uncoupling and coupling the cable for segment removal and installation. An attractive alternative is to have both the sense and drive electronics on the same side of the gap (same segment) and capacitively couple the signals across the gaps. This will require additional capacitors. A detailed design of the complete capacitor system will be made in the coming year as part of the technology development program.

CELT Displacement Sensor - Electronics

We expect the CELT displacement sensor electronics to be similar to those used for Keck (Gabor, 1983, and Meng *etal.* , 1990). The cost of 16-bit ADCs are now lower and these will be used in place of the 12-bit AC used for Keck. This will provide greater offset and operating ranges.

4. ACTUATORS

Actuator Requirements

Although the design of the mirror cell has begun, we do not know yet the stiffness or sag in going from zenith to horizon. For now we assume the sag will be 1 mm, and that the shape of the deformation will dominated by quadratic changes. This implies a maximum actuator velocity of about 40 nm/s.

The gravity-induced motion will be extremely smooth over the primary. The resulting geometric optics image blur induced is under 0.008 arc seconds/second. Hence corrections may be applied as slowly as once every 10 seconds and still maintain the seeing-limited image quality of the telescope.

Again, since the changes are very smooth, these errors do not need to be corrected frequently for adaptive optics use. The AO system will easily accommodate more than 10 seconds of deformation. However, for AO, smoothness is the critical concern. The applied motions must be made smoothly, as step errors between segments will degrade the Strehl ratio, and should be kept below 10 nm.

We set a goal that differential actuator errors be less than 5 nm rms (driven largely by AO, but also to a lesser extent by seeing-limited requirements).

If the error, δp, in the actuator motion, is proportional to the commanded move, p; the actuator velocity, V, is 40 nm/second; and the actuator update time is T; then $\delta p = \alpha p$ and our noise requirement implies

$$\delta p = \alpha TV < 5 \text{ nm rms}.$$

If moves are made to 3%, then T can be as long as ~ 4 seconds.

We expect the mirror cell deformations to vary extremely smoothly over time and nearby actuators to have very nearly the same errors. Thus, to achieve relative position errors below 5 nm rms, will require either moving the actuators up to 8 times per second, or moving the actuators at constant velocity. Depending on the solution, the control loop may have to operate at up to ~ 5 Hz.

The requirements for the actuators used in the Keck telescopes (Gabor, 1983, and Meng, *etal.*, 1990) are listed below along with the estimated CELT requirements.

	Keck	**CELT**
Range	> 0.6 mm	> 1.2 mm
Rms posiition error (O Hz)	< 20 nm	< 7 nm
Slew rate	> 10 microns / sec	> 10 microns / sec
Transverse load capacity	> 14 kg	> 5 kg
Axial load capacity	> 150 kg	> 30 kg
Axial stiffness	> 5.9 x 10^7 N/m	> 1 x 10^7 N/m (~100 Hz resonance)
Transverse stiffness	> 12.7 x 10^5 N/m	> 1 x 10^5 N/m
Local power dissipation	< 10 W	< 2 W

For CELT our baseline requirements are more stringent for noise and resolution. Due to the greater gravity-induced formation of the mirror cell, the required range for the CELT actuators is larger than for Keck. Initial estimate suggest the cell deformations can be kept to only about two times that of Keck. We assume for now this factor of two giving a required actuator range of 1.2 mm.

The Keck actuators carry the axial load of the segments. The CELT baseline segments weigh 74 kg, and the Keck segments weigh 400 kg. If the actuators carry this axial load, then the load requirements above can be reduced by a factor of 5.4. An alternative, described below, would carry the load through a lever, and these requirements would be further reduced by the mechanical advantage of the lever.

Keck actuator design

The Keck position actuator design is shown schematically in Figure 6. A local servo (torque motor and rotary encoder) controls the rotation of a precision roller screw (pitch = 1 mm) and drives to a commanded number of counts. This drives a nut that moves the output shaft through a 24-to-1 hydraulic motion reducer. The hydraulic reducer allows the screw/nut to move distances large enough to avoid stiction and breakaway problems. The output shaft is supported in the transverse directions by two stainless steel corrugated diaphragms. The least count motion of the actuators is 4.2 nm. Despite the complexity of the system, the actuator failure rate is extremely low.

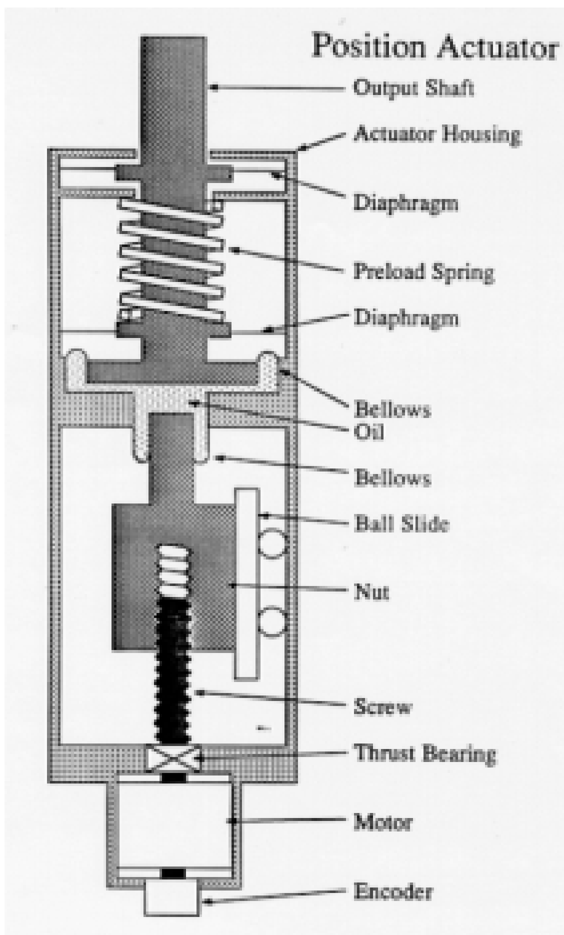

Figure 6. Schematic of the actuator design for the Keck telescopes

CELT Actuator

Although the Keck actuators are highly successful, they were complex and expensive to build. We are actively studying alternatives for CELT. Two general directions are being studied; 1) Two-stage actuator systems and 2) lever-actuator systems.

Two-stage Actuator System

Achieving actuator range/step size of > 100,000 is a challenge for many kinds of actuators. The Keck actuators are capable of this, but given our desire to minimize costs, we seek an alternative option. One way to possibly achieve the general goals is to use a two-stage actuation system.

Since CELT has roughly 1000 segments, the routine handling of segments for re-coating is a key issue. At Keck, segments are installed and removed from the telescope one at a time. For CELT this is impractical, and we plan to handle segments in groups or clusters. Each cluster will be supported on a raft that can be installed or removed as a unit. Currently we expect each raft will support 19 segments, for a total of roughly 60 rafts. Each raft will be supported on three actuators whose central task is to raise the raft above its neighbors so it can be coupled to a crane for removal and installation.

These actuators may be able to perform an additional function. Ball screw actuators are widely and economically used in the commercial world. Such actuators are excellent candidates for moving rafts. In addition, they can move very smoothly, with noise levels of about 10 µm.

In a two-stage system, individual segment actuators can have reduced a range requirement, if the raft actuators are used to dsrive the bulk coarse segment motion. For the assumed rafts, gravity deformations within the raft will be quite small, of order 10 µm.

All fine motion can be carried out by the segment actuators, and periodically (when they run out of range) the raft is moved by the raft actuators, and the segment actuators revert to their original positions. During this double motion, we expect that the segments will not be positioned to the desired tolerance. Thus, periods of double motion should be minimized. We suggest that restricting such motions to be no more than once per hour will allow such moves to be made when science detectors are being read or moves to another object are being made, and thus will not require any additional observing time. Using the above worst case values suggests that a segment actuator range of 200 µm is more than sufficient. Thus should significantly increase the number of potential segment actuator options.

For two stage actuation it appears that piezo actuators are an interesting and potentially economical option. We are currently exploring several commercial alternatives.

Lever-Actuator System

In the later stages of the Keck design we considered an alternative actuator design that used a commercial actuator acting through a lever to reduce the motion applied to the mirror (Mast and Nelson, 1985). This design has a number of advantages. The cost of commercial devices is often lower than for specialty designed and built hardware. The lever with a flexure pivot is potentially more stable and robust that a hydraulic system. The disadvantages that led to the final selection of the specialized hydraulic actuator for Keck included 1) timing in the project schedule, 2) packaging into the existing segment support design, and 3) the robustness/lifetime of commercial actuators.

The Hobby-Eberly Telescope uses a similar lever-actuator system. However, their effective step size is 21 nm which does not meet the CELT requirements.

From the new perspective of CELT this actuator design looks attractive. A lever-arm motion-reduction factor of about 10 to 15 is feasible and would reduce stiction and breakaway problems when making small mirror motions. The Keck scheduling and packages issues are not relevant to CELT. Since the CELT segments are about five time lighter than the Keck segments, the load on the actuator is smaller. This should allow a longer life. However, the proposed update rate for the active control is higher, and so the actuator needs to be faster, and this will affect the lifetime.

We are currently making a survey of commercial actuators, and the design of the lever actuator system will be actively pursued this coming year.

5. TECHNOLOGY DEVELOPMENT PROGRAM

Two important goals of the CELT technology development program are:

1) Design, build, and test prototype sensors

   Prototypes of the sensors described above will be designed, built, and bonded to Zerodur. The performance will be tested, including temperature sensitivity and long term stability.

2) Design, build, and test prototype actuators

   Commercial actuators will be tested extensively for noise, stiction, and lifetime.

The goal of both these programs is to obtain an accurate estimate of the cost of the systems required for CELT.

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