Title
MIRROR FIGURE CONTROL PRIMITIVES FOR THE KECK OBSERVATORY TEN METER PRIMARY MIRROR

Authors
Meng, J.D.
Minor, R.
Merrick, T.

Publication Date
1989-09-01

LBL-25959

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

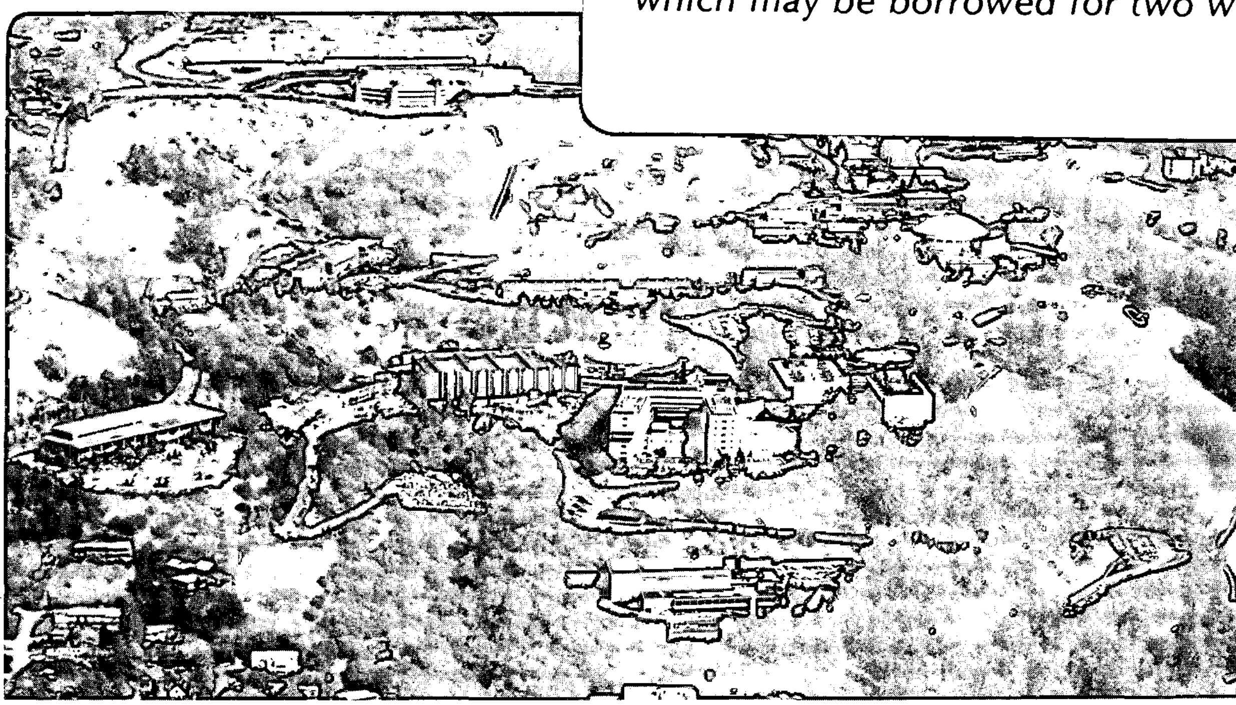
Engineering Division

Presented at the Technical Symposia on Aerospace Sensing, Orlando, FL, March 27–31, 1989, and to be published in the Proceedings

Mirror Figure Control Primitives for the Keck Observatory Ten Meter Primary Mirror

J.D. Meng, R. Minor, and T. Merrick

September 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

LBL-25959

Mirror Figure Control Primitives for the Keck Observatory Ten Meter Primary Mirror

J. D. Meng, R. Minor and T. Merrick

Engineering Division, Lawrence Berkeley Laboratory
1 Cyclotron Road, Berkeley, California 94720

ABSTRACT

The Keck Observatory primary mirror is comprised of 36 segments from which 216 glass temperatures and 168 measures of relative displacement are continuously read. Mirror figure adjustments are under the active control of 108 adjustable-length actuators, three per segment. We describe our collection method for mirror segment displacement data and glass temperature data and the supplying of individual control signals to the actuator controllers and sensor electronics, both located near each mirror segment, and discuss the mirror's computerized control system. Much of the sense and control electronics is close to the rear surface of the primary mirror. From an historical perspective, we describe the impact of the need to minimize heat sources and cabling, on the communications method used and on its implementation. We conclude with a brief structural overview of the hardware in use to actively maintain primary mirror figure.

1. INTRODUCTION

Primary mirror figure is set from star observations during calibration. Maintaining this figure requires remembering the mirror relative positions set at calibration time, detecting changes and then appropriately reorienting the mirror segments. Figure 1 shows a piece of the mirror with displacement sensors, temperature sensors, actuators and the local electronics box. It is not drawn to scale. Capacitive displacement sensors bridge the gaps between mirror segments. Two displacement sensors bridge each gap, producing (via appropriate electronics) numeric values proportional to the location of the edge of the first segment relative to that of the second segment in the segment piston dimension. Since the capacitive sensing pads are not actually centered on the gap, but are displaced away from the edge of each segment, sensor readings also change if the two adjacent segments rotate relative to each other on an axis defined by the center of the gap. Corrections to displacement sensor readings are necessary depending on the angle of the telescope's axis above the horizon and depending on temperature changes as measured by temperature sensors attached to each segment. For a complete discussion and analysis of the concepts behind maintaining mirror figure, see Refs. 1-4.

Each temperature sensor (a precision thermistor) generates a number (via appropriate electronics) correlated with its temperature . Each mirror segment's glass temperature is monitored in six locations. One additional temperature sensor is positioned to measure the temperature inside the box containing the segment's electronics, and an eighth temperature reading is of a fixed-value resistor used as a reference. Consequently, mirror segment temperature measurement requires reading 36 x 6 = 216 values plus 36 reference values. In addition, 36 temperatures are read to monitor electronics heating, bringing the total number of readings to 216 + 36 + 36 = 288.

Although each segment has twelve displacement sensors (two on each of its six sides), they are shared by adjacent segments, so readout is of six per segment. Since innermost segments and outermost segments do not have six neighbors, they do not have the full complement of displacement sensors, so only 168 displacement sensors are read from the entire mirror. In addition to translating sensor readings, each displacement sensor electronics module also controls sensitivity and offset for its sensor. For the 168 preamps, sensitivity and offset requires 2 x 168 = 336 settings.

Repositioning the mirror segments once a figure error is detected is accomplished by changing the distance from one or more of a mirror segment's attachment points to its subcell support. Each mirror segment sits on a fixed center post (Radial Support) about which it may be tilted by the action of any or all of three actuators arranged in a triangular configuration about the center post. The mirror segment may also be moved a short distance in piston owing to the flexibility of the attachment to the center post. Each of the three actuators (via appropriate electronics) independently changes its length on

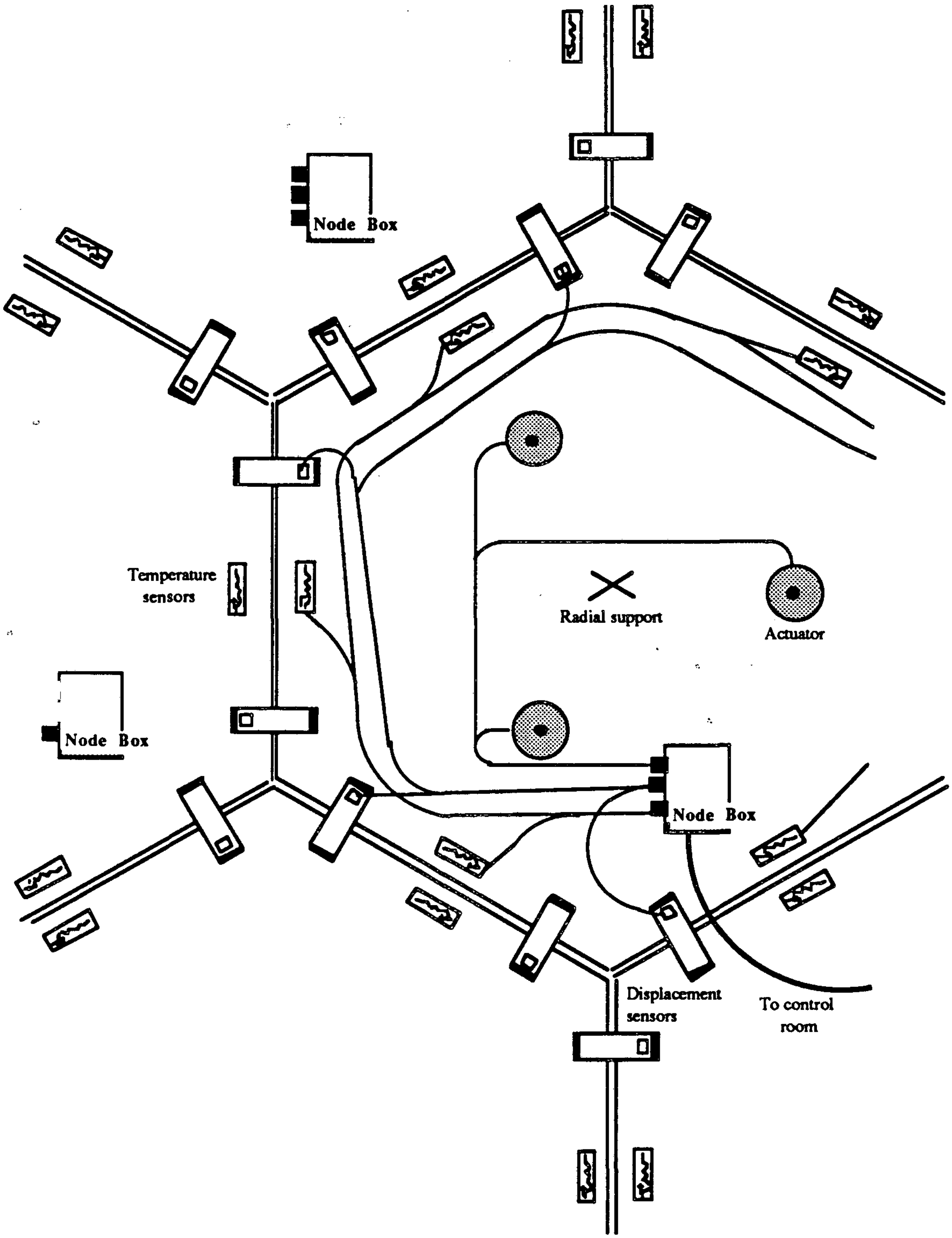


Figure 1: A closeup sketch of a section of the main mirror with one segment cabled, showing gaps between segments, the relative positions of temperature and displacement sensors and of actuators, and their connections to local electronics, housed in the Node Box. Each segment has its own Node Box. Each Node Box has its own umbilical cord to the computer room in order to receive power and to communicate. Not to scale.

command. For the entire mirror, there are 36 x 3 = 108 actuators to control. Each of the 108 actuator electronics modules also monitors happenings in the actuator and in its electronics and continuously reports status.

To summarize, the primary mirror is continuously monitored for temperature, and for segment edge-displacement (with respect to adjacent segments). The displacement sensor electronics must have its sensitivity set and it must be electronically set to balance its sensor's output. Each actuator needs to be told how far to move and in what direction, and the response of each actuator needs to be monitored. In addition, a unique electronic reset may be transmitted to each mirror segment. These are primitives needed to monitor mirror performance and make mirror adjustments. For the entire mirror, 564 values need to be continuously read, and 480 corrections need to be periodically returned.

The system design is constrained in several ways:

1) Heat generation in spaces close to the primary mirror needs to be minimized. Otherwise, there is the possibility of image degradation due to air convection.
2) The amount of cabling needs to be minimized, not only as an economic constraint (the mirror and the control room are about 100 meters from each other) but since the cable bundle is wrapped around the telescope's main bearings, its physical size and flexibility are critical.
3) To enhance reliability, the electronics parts count was minimized by using VLSI devices and EPLDs (Electronically Programmable Logic Devices) where practical. The mirror control system is modular with a granularity which permits module replacement when a failure occurs and subsequent repair in a separate maintenance facility. One such module is the electronics box (the Node Box) attached to each segment. Software primitives, in conjunction with hardware-generated reports, perform fault localization to the replaceable module.
4) Since the design value of the capacitors is only about 2 pf, electronic translation of the differential capacitances from the displacement sensors, requires that the electronics be close to the sensors. The actuators move in steps of a few nanometers and to be able to successfully control what the actuator does and monitor its performance reliably requires that actuator electronics be close to the actuator.

2. SYSTEM OVERVIEW

Early on in the project, a test setup was built and successfully run to verify the viability of the electronics and hardware needed to make the mirror perform satisfactorily.[2] For this technical demonstration nearly all the electronics was kept far away from the mirror, the only exception being an FET buffer mounted next to each displacement sensor. In discussions regarding the eventual physical configuration of the system, we explored the other extreme - that of putting most of the electronics in the immediate vicinity of the mirror. Digital signal transmission schemes, ranging from a single serial link servicing everything on the mirror to a completely parallel connection to the control computers, were considered. In the end, we compromised, as shown in Fig. 2. Each mirror segment has its box of electronics, close enough to the sensors and actuators to thwart potential problems arising from long cable runs containing high-precision analog signals. Each Node Box interfaces the analog of the mirror to its private serial link with the central computer facility.

Using a serial link reduces the wire count enough to solve cable size and flexibility problems, even with 36 cables (one per Node Box) in the bundle. Since cable drivers/receivers are the major source of heat in the electronics, the serial link helps solve the heating problem by reducing the number of signal connections from each mirror segment to its computer to just five.

The Node Box centralizes data gathering and distribution for a segment. It is where serial data from the control computers is converted into parallel form and distributed to action-oriented modules such as actuator controllers or sensor preamps. In the other direction, it gathers inputs from the actuators and sensors, digitizes them and sends them to the central computers.

Displacement sensor and temperature sensor analog signals are cabled into the Node Box where signal conditioning and digitization occur. Each displacement sensor uses a dedicated module. All the temperature sensors feed a single common module which also supports the control and communications electronics for the Node Box. Figure 3 is a sketch showing the contents of a Node Box.

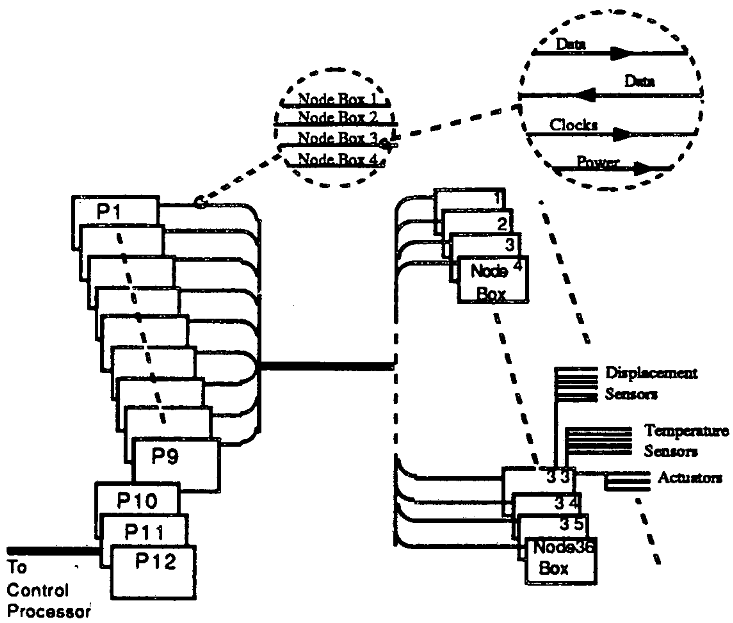


Figure 2: System structure showing the 12 control computers and their connections to the mirror electronics and to the control processor. Processors P10 and P12 are dedicated to computation and monitoring. Processor P11 communicates via ethernet with the control processor which runs the operator interface.

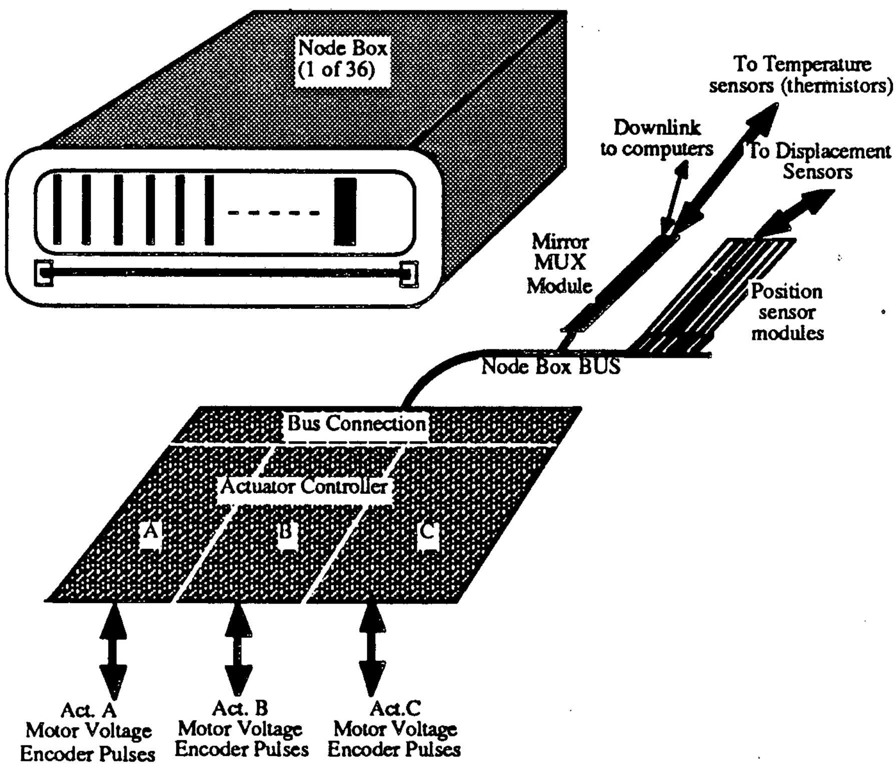


Figure 3: Inside a Node Box, showing the displacement sensor electronics modules, communications module and actuator controllers (all three are on a single printed circuit board). Communications inside the Node Box take place over a custom internal bus.

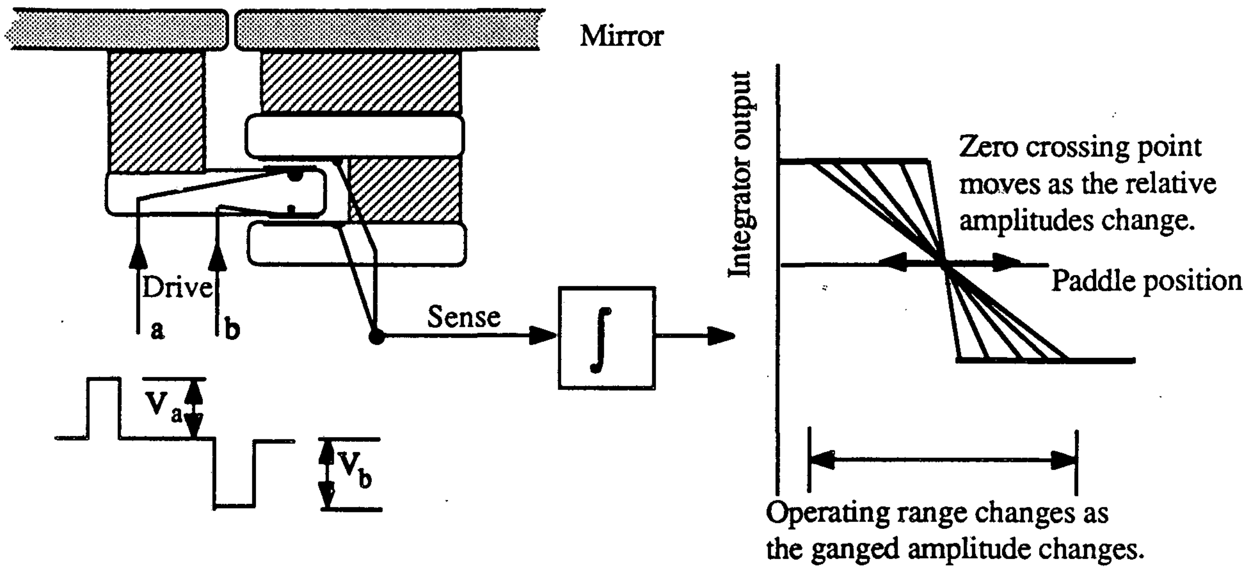


Figure 4: Primitives are in place to change the ratio of drive voltage V_a to that of drive voltage V_b, and also to change the drive voltages in ganged fashion so that the ratio remains fixed. The displacement sensor forms a pair of differential capacitors. When the drive voltage amplitudes are changed so the ratio remains fixed, the net effect is to adjust the sensor sensitivity. If the ratio is changed, the net effect is to adjust the offset of the sensor null point.

Displacement sensor analog signals enter modules whose function is to produce a digital output. The module controls the amplitude of the drive signals to the two capacitors on the sensors and also controls the relative amplitudes of the two signals. In the first case, the net effect is to adjust the sensor sensitivity; in the second, the net effect is to adjust the offset of the sensor null-point. There is one module for each of six displacement sensors. Figure 4 is a sketch of a displacement sensor and its signals.

Every time the displacement sensors are read, each of the three actuator control modules is read to determine what is happening with the actuators. Actuator controller data is either digitized (actuator motor current) or in digital form on the controller card, and is transferred over the internal Node Box bus as parallel data bytes into the Multiplexer module for serialization and transmission.

Digital data from the control room arrives in the Node Box in a serial stream. The Node Box Multiplexer converts the serial stream into parallel data, decodes its destination and produces the proper bus signals to send it there.

Signals from the 36 Node Boxes converge on the control room via 36 multi-wire cables. Power supplies and regulators, because they are major sources of heat, are located in the control room and the regulated power is fed via the connecting cables to each Node Box. The Node Box contains passive filtering for power and over-voltage and transient protection, but no active filtering. Since the current drain of Node Box electronics is very stable, the long cable between power supply regulators and electronics does not destabilize voltage levels. Power wiring to the Node Boxes surrounds the signal wires in the same cable. The two are separated by a shield layer.

The central part of the mirror active control is the 12-computer array in the control room. Data fans into the computers like the limbs in a tree structure, and fans out in the reverse. Of the 12 computers, nine handle the connections to the Node Boxes with four high-speed asynchronous serial DMA (Direct Memory Access) links each. Each serial link is controlled by a UART (Universal Asynchronous Receiver Transmitter) operating at 250 kbaud.

3. DATA MOVEMENT ON A SEGMENT

The serial data radiates to the segment node boxes as bit-serial streams of bytes (8 bits). In addition, a BREAK signal may be sent to any or all of the Node Boxes to initialize the Node Box circuitry. The BREAK signal is merely a long-interval assertion of the data line, interpreted by Node Box hardware.

Data fanout on a segment actually occurs within the Node Box which contains a custom internal parallel bus. Individual cables from the node box connect to each sensor, actuator and temperature sensor.

As mentioned above, 12 computers in a central location about 100 meters from the mirror close the loop from sensors to actuators, actively maintaining the figure of the primary mirror. Of these 12, nine do input and output. These nine also perform front-end filtering on data arriving from the mirror. Of the three remaining computers, one is responsible for performing the calculations needed to translate sensor readings into actuator corrections, one handles operator connections to the mirror and the last monitors the performance of the system.

A hardware clock drives data collection from the mirror without software intervention. Software primitives set clock frequencies and turn the clocks on and off. A burst of data 40 bytes long arrives at each of the input/output processors every 10 ms. The completion of the simultaneous accumulation of data from all the 36 mirror segments triggers a sequence of events which ultimately results in move commands being sent back to the actuators. Fifty inputs are required to produce one set of actuator command outputs, resulting in a mirror figure correction every 1/2 second.

At the most primitive level, each actuator may be moved in a specified direction in a specified number of four nm steps. Feedback from the actuator and its controller permit developing higher-level primitives. The actuator controller maintains a step count with zero as the shortest actuator length. One primitive resets this counter by retracting the actuator until an end-sensor is tripped, resetting the counter and then enabling counting to start when the actuator drive motor next crosses an index position while extending the actuator.

At maximum gain, position sensor electronics are unsaturated, producing variable outputs, for about 12,000 nm in each direction. The sign of the output is the only information available when the electronics is saturated, indicating the direction of travel needed to reach the unsaturated region. As the electronic sensitivity of the sensor preamp module is reduced, this region widens, and adjusting the electronic offset moves the region along the axis of sensor relative displacement, as seen in Fig. 4.

The six modules generate hardware flags after digitizing, and a central module (the Multiplexer) in the Node Box sequences and collects data from the six. Data collected is immediately serialized and shipped out of the Node Box over the long cable to the control room. Figure 5 is a sketch of the timing of these processes. Temperature sensors feed an analog switch on the Multiplexer module, the output of which is digitized, serialized and sent to the control room. Only one temperature sensor is read at the time six displacement sensors are read, so all the displacement sensors will be read eight times for every complete scan of temperature sensors.

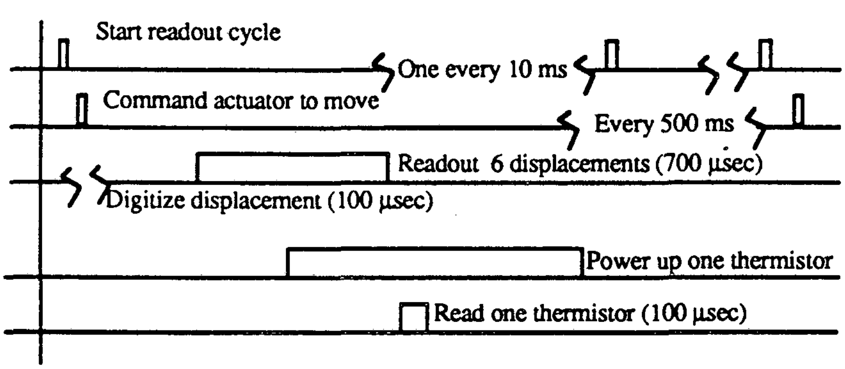


Figure 5: Signal sequencing and repeat intervals for the mirror control. The 100 Hz burst rate for data downloads from the mirror is hardware controlled from a clock in the multiprocessor crate in the control room. Uploads to the mirror are under program control and will normally occur at 500 ms intervals.

The three actuators on each mirror segment share one printed circuit board and its bus connection. However, the control electronics for the three are separate. As was mentioned earlier, the actuator control primitives specify the number of 4 nm steps to move and the direction of the move. The controller for an actuator monitors each move and sends back information about the move's progress and about the actuator. Such information includes instantaneous motor current, the contents of a counter which is counting each step of the move as it occurs, a flag when the actuator is completely retracted, a flag when the move is complete and flags indicating on which side of completion the actuator is. One additional returning value is the number used by the controller hardware to set motor current. These returning values are the source of primitives which read an actuator's length, if an actuator has finished a move and the actuator's health.

Mirror temperature is not expected to change very rapidly, compared with values from the displacement sensors. So, only one of the values from the eight temperature readings (two of which are not mirror temperature) is attached to the packet when six displacement sensors on a mirror are read every 10 ms. In order to get eight temperature readings, the displacement sensors must be read eight times. The software primitive sorts all this out, and returns the reading from any specified temperature sensor on demand.

Relative displacements of all mirror segment edge pairs arrive at the processor array every 10 ms under the control of a hardware clock, as mentioned above. Each of these values is available on demand. In each input processor, digital filtering of the incoming data streams (four per processor) occurs. The outputs of these filters are available via primitives. Generating the needed actuator moves means performing a matrix multiply, and the result of this is also accessible via primitives.

SUMMARY OF PRIMITIVES

Primitive	Points of Application
Read Displacements	168 segment relative edge positions
Read Temperatures	216 glass temperatures 36 electronics temperatures 36 references (1 per segment)
Set Displacement Sensor Sensitivity	168 sensor drive voltages
Set Displacement Sensor Offsets	168 sensor drive voltage ratios
Move Actuator	108 (Single command contains distance and direction)
Read Actuator Condition	108 sets of values, including: Actuator move status & Actuator motor current
Read Actuator Absolute Position	108 values, each representing the length of an actuator in ≈ 4 nm steps

4. CONCLUSIONS

The Keck Observatory ten-meter primary mirror houses a set of low-power front-end electronics to perform the jobs of transforming sensor capacitance values and mirror temperature values into digital data which is serially transmitted to a remote multi-processor system for conversion into move distances and directions for the actuators making adjustments to the mirror figure. The front-end electronics also forms a local control loop for each actuator which accepts digital commands and performs the requested lengthening or shortening maneuvers. Electronics in the physical vicinity of the mirror is divided into 36 identical subsystems, one per mirror segment, each of which communicates serially with an input/output processor located remotely. This configuration forms what we believe to be a good compromise between the needs to minimize power loss and cabling near the mirror and the need to place critical electronics close to the sensors and actuators mounted on the back side of the mirror glass.

Primitives built into the software and using the available hardware permit access to data as it flows into, out of and through the control loop for the mirror. These primitives are the building blocks for performing mirror figure control and for monitoring the behavior of the system and its environment, and permit higher-level software to detect and pinpoint failing modules.

5. ACKNOWLEDGMENTS

We wish to acknowledge the considerable contributions of the many people involved in the realization of this project; in particular, R.C. Jared, J. Franck, H.G. Jackson, A.A. Arthur and G. Gabor. This work was performed under the auspices of the U.S. Department of Energy, Contract No. DE-AC03-76SF00098; it was funded by California Institute of Technology, Contract No. 670012. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

6. REFERENCES

1. Jerry Nelson, Terry Mast and Sandy Faber, ed., The design of the Keck Observatory and telescope (Ten Meter Telescope) (1985).

2. Jerry Nelson, Michael Budiansky, George Gabor and Terry Mast, "The segmented mirror control system prototype for the TMT: Status report", SPIE, 444, p. 274, in Advanced Technology Optical Telescopes II (1983).

3. Terry Mast, George Gabor and Jerry Nelson, "Edge sensors for a segmented mirror", SPIE, 444, p. 297, in Advanced Technology Optical Telescopes II (1983).

4. George Gabor, "Actuators for a segmented mirror control system", SPIE, 444, p. 287, in Advanced Technology Optical Telescopes II (1983).

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720