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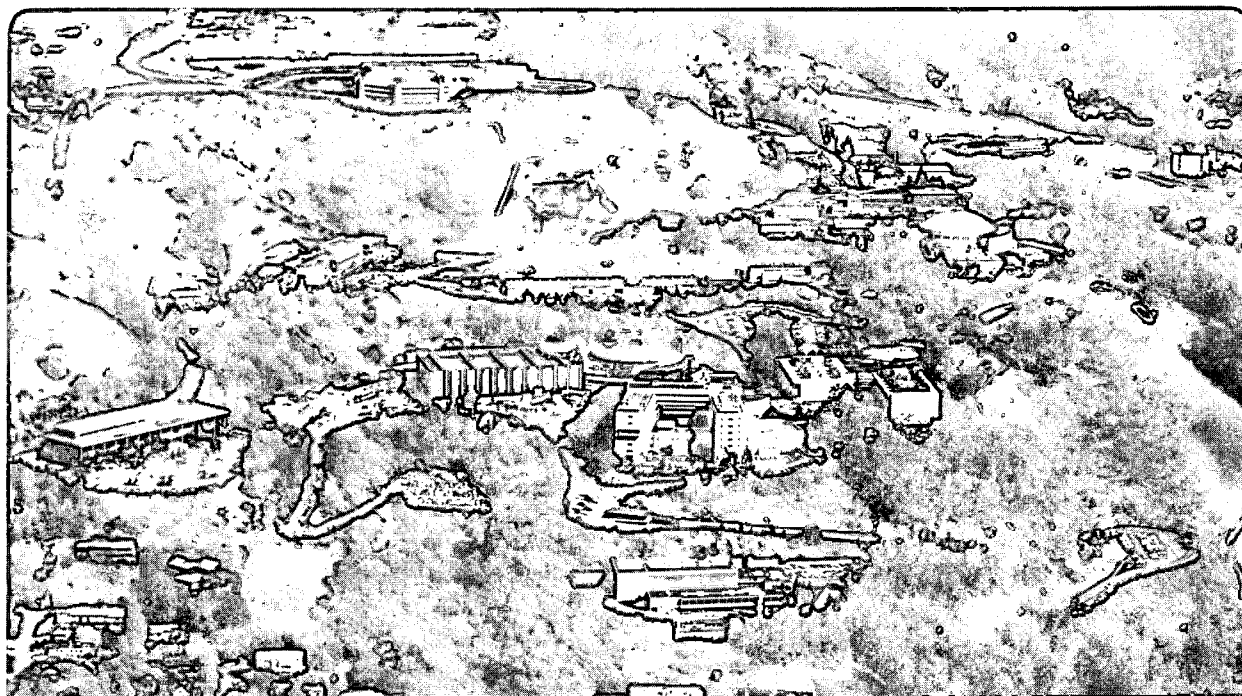
## Engineering Division

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### An Emulator for the W.M. Keck 10m Telescope

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An Emulator for the W.M. Keck 10m Telescope

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## An emulator for the W.M. Keck 10m telescope

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### ABSTRACT

The W.M. Keck Observatory Ten Meter Telescope has a Segment Alignment Control System (ACS) to achieve the necessary optical quality over the primary mirror. The primary mirror is a hyperboloid made with a mosaic of 36 segments. The attachment of the primary mirror to the mirror cell is made through 108 actuators of adjustable length. The measurement of the relative position of the segments is carried out by 168 capacitive displacement sensors which provide input to the control system. The piston displacement and tilt angles of each segment are actively controlled by a digital multiprocessor system that executes the control laws.

This paper presents an emulator to test the Segment Alignment Control System of the Keck telescope. The Emulator replaces mirror segment hardware (actuators, sensors and segments) with timed software loops that appear to the rest of the ACS as the real mirror hardware:

The mirror segment hardware has been modelled by taking into account the discrete-time characteristics of the digital controller. The functions are parametrized in a way that the operator can change the parameters to adapt the configuration of the emulator to the changes of structure, and to new knowledge of the behavior of the system elements as it is acquired in real tests. The emulator is programmed in one of the twelve microprocessors of the ACS hardware and the system can function in the emulation mode by an operator command.

### 1. INTRODUCTION

The principal characteristic of the W.M. Keck telescope<sup>1</sup> is that its 10 m diameter primary mirror is divided into a mosaic of 36 hexagonal segments. The spatial orientation of each segment is actively controlled with a high degree of accuracy so that the combined reflecting figure can approximate to a hyperboloid. The active control of the segmented structure is carried out by the Segment Alignment Control System (ACS) to maintain at all times the correct alignment of the controlled segments with respect to their neighbors compensating for mechanical deformation and distortion effects due to gravity, slowly varying thermal gradients, attitude dynamics, and low frequency external disturbances.

The telescope has a support structure, or mirror cell, that operates as an almost fixed base for the primary mirror. The attachment of the primary mirror to the mirror cell is made through 108 actuators of adjustable length. Each segment is oriented individually by three actuators that displace the segment in three degrees of freedom: a translation along the mirror axis, or piston, and two out-of-plane rotations, or tilts. The other degrees of freedom are constrained by a thin, flexible diaphragm.

The actuators have a rotary optical encoder that measures their shaft elongation. Data from actuator encoders are used in the control software to define the mirror position relative to the mirror cell by calculating three linear combinations of the 108 actuator encoder readings.<sup>2</sup> Each actuator has its base end on the mirror cell (Fig. 1). The link between the actuator shaft at the other end and the segment is made through a flexible structure, the whiffletree, designed to apply the force to the segment through enough points to minimize local deformations and to achieve an approximately uniform axial segment support.

The resulting position and orientation of all the segments is measured by 168 capacitive displacement sensors mounted near the segment edges. Those measurements provide the feedback to the control system that commands the actuators. Control

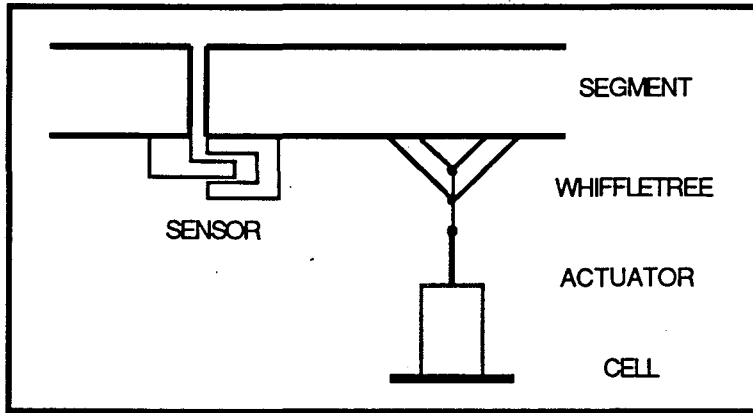


Fig. 1: Segment mirror structure

laws are programmed in a multiprocessor system. The main inputs of the control system are the measurements of the relative displacements between adjacent segments (Fig. 2). Data from the sensors are compared with reference data, obtained through an off-line calibration procedure, and the control law provides the commands for the actuators.

Sensor signals are amplified, discretized by analog to digital converters and packed by sensor electronics that are placed close to each segment (Fig. 3). The packed data, or downlink packets, are sent by serial links to the multiprocessor control system at a 100 Hz rate. The input processors unpack downlink packets and filter sensor readings to synthesize filtered sensor data. The control algorithm finds the error between references and measurements at a 2 Hz rate, calculates rotational and axial incremental displacements and generates the commands to the actuators to reduce the error, i.e., to reorient the segments in order to bring the optical surface into the desired figure. The commands to the actuators are also packed (uplink packets) and sent by a serial link to actuator electronics that are placed close to the segments.

## 2. SEGMENTED MIRROR EMULATION MODEL

The Segment Alignment Control System<sup>3</sup> is being developed at the Lawrence Berkeley Laboratory of the University of California. It consists of sensors, sensor electronics, multiprocessor computer system, actuators, actuator electronics, and control software (Fig. 3). One of the problems in testing the design is that the mirror system will not be available until its installation in the mountain site in Hawaii, so there is no physical way to test the computer control system until that time. To solve that problem an emulator of the segmented mirror hardware has been designed and implemented to debug and test the control software. The emulator replaces mirror segment hardware (actuators, sensors and segments) with timed software loops that appear to the rest of the ACS as the real mirror hardware.

With the emulator it is possible to demonstrate in the laboratory the full and consistent operation of the multiprocessor control system. Debugging of a large multiprocessor control software application can be a formidable task. Emulating the segmented mirror structure offers significant debugging capabilities. Some of the salient characteristics of the emulator are:

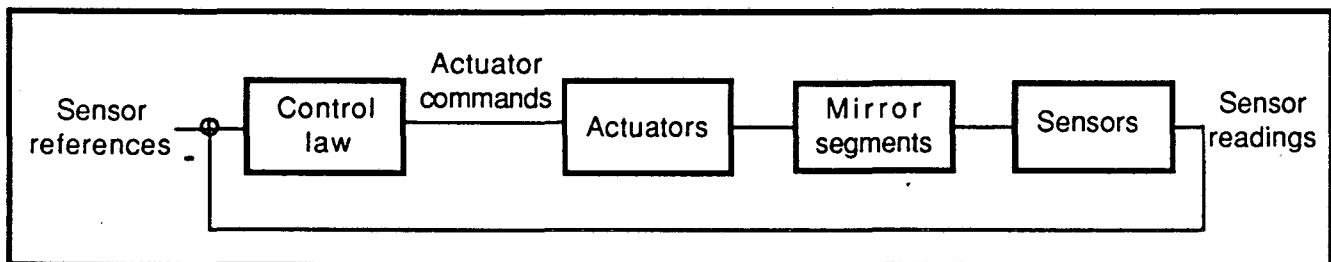


Fig. 2: Control system block diagram

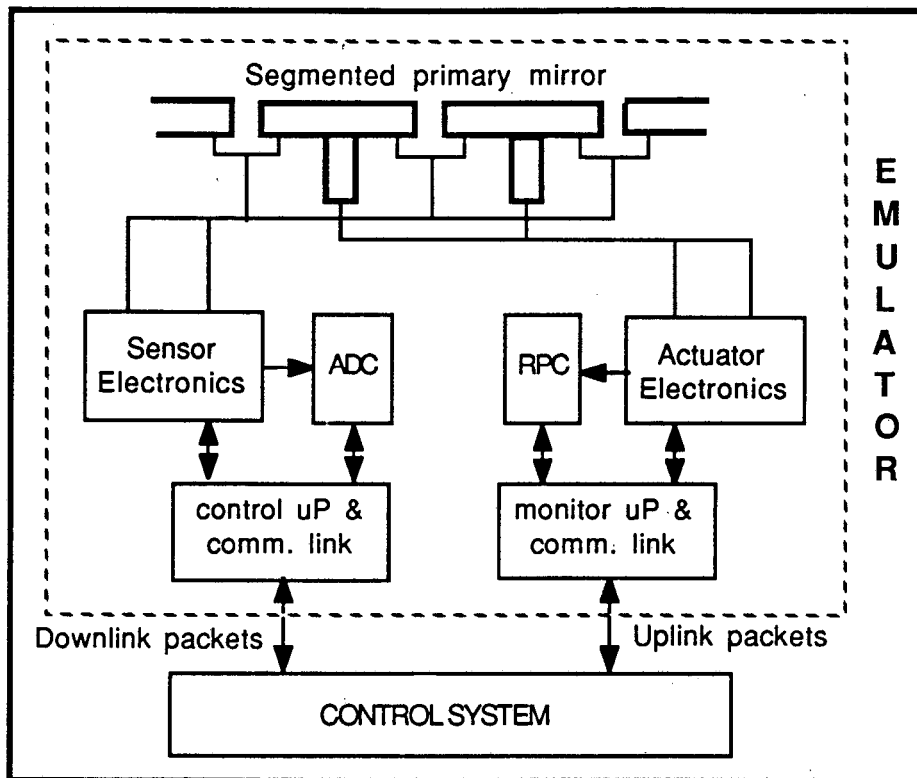


Fig. 3: Mirror Emulation System

- a) Full simulation of mechanical operation including all moving parts that affect I/O
- b) Open loop and closed loop test of the system
- c) Selection of portion of the structure to test different conditions of the system
- d) Generation of test functions to be used as mirror perturbations or noise
- e) Data acquisition of the relevant variables of the mirror hardware
- f) Model parameters redefinition

The main objective of the emulator is the test of the hardware and software of the multiprocessor control system. We can devise two levels of test: the static or operational test, and the dynamic or functional test. The static test is a first level of debugging of the logical operation of all the programs included into the multiprocessor system, i.e., to detect blockings, loops, inconsistencies, etc., and to debug the multiprocessor hardware, to detect timing problems and malfunctions. The emulator will operate in open loop and will provide sensor data to feed the control system in a deterministic way. The dynamic test permits the evaluation of the dynamic properties of the control algorithm, based on the response of the system to external perturbations generated at the mirror. For dynamic test, the emulator will operate in open or closed loop and it will be possible to determine time-dependent characteristics and performance of the control laws in terms of position or velocity errors, settling time, etc. These dynamic characteristics give a measure of the surface figure or image quality.<sup>4-6</sup>

### 3. EMULATOR STRUCTURE

The emulator follows the structure of the segmented mirror hardware and has the block diagram of Fig. 4. We can consider two sections in the emulator, with dimensions 108, the number of actuators, and 168, the number of edge sensors, respectively. A geometric matrix models the segmented mirror system. It defines the displacements of the edge sensors as a function of the displacements of the segments at the projection of the actuator supporting point, and changes the dimension of the subsystems from actuator dimension to sensor dimension.

The principal inputs to the emulator are the actuator commands that the control system generates each 0.5 s. The actuator gain block convert the commands into nanometer units and the actuator dynamics block gives the temporal displacement of

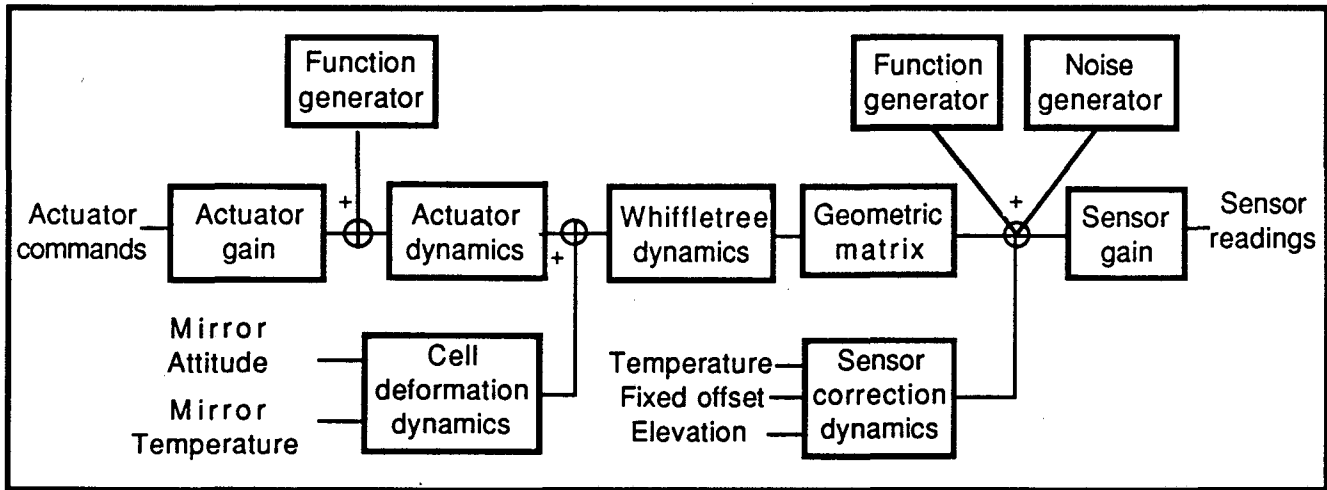


Fig. 4: Emulator block diagram

the actuator shafts, i.e., how the stepping motors and hydraulic bellows respond to the commands. The whiffletree dynamics block includes the temporal relations of the mechanical links between the actuators and the segments, and the couplings produced by the displacements of the segments and deformations of the mirror cell from the actuators forces. We have considered this block as a square matrix of dynamic relations. But the effects between adjacent actuators or whiffletrees are small enough<sup>7</sup> that the resulting matrix is diagonal dominant. For purposes of emulation we can consider only the diagonal terms, resulting in 108 uncoupled parallel relations.

Temperature and telescope orientation modifies the shape of the mirror cell, so we have considered their effects as additive axial displacements of the actuators reference plane.

Sensor edge measurements are calculated through the geometric matrix from the displacements of the segments at the actuator supporting points. The additive effects on the sensor measurements given by the temperature, elevation and offset are superimposed from the sensor displacements. The sensor gain block converts the sensor measurements in nanometer units to analog to digital converter units.

The loop can be opened after the actuator gain block or after the geometric matrix block. In this way it is possible to test the open loop operation of the system taking as test input signals the ones produced by the function generator blocks. The purpose of the function generators is to introduce perturbations (impulse, step, ramp, oscillation) at the actuators and at the sensors to test the dynamic response of the control programs. A noise generator is added at the sensor to test the noise characteristics of the system.

Sensor readings of the real system are obtained at a 100 Hz rate. The mathematical model of the emulator discretizes the dynamic functions at that frequency. We have considered all those functions as linear, time-invariant and discrete. A different alternative would have been to use continuous functions in the mathematical model and sample its results. The discrete model is accurate at the sampling points, however, and computationally easy and fast. Another advantage of this formulation is that the discrete functions can be parametrized in a way that the operator can easily change to adapt the configuration of the emulator to the changes of structure, and to new knowledge of the behavior of the system elements as it is acquired in real tests.

The temporal form of the discrete functions is formulated as an infinite impulse recursive (IIR) filter. We have programmed 108 fourth order IIR filters for the actuator motors and 108 for the whiffletrees, and 108 second order IIR filters for the cell deformations and 168 for the sensor corrections. The structure of a fourth order IIR filter is:

$$y(k) = b_0 x(k) + b_1 x(k-1) + b_2 x(k-2) + b_3 x(k-3) + b_4 x(k-4) - a_1 y(k-1) - a_2 y(k-2) - a_3 y(k-3) - a_4 y(k-4) \quad (1)$$



where  $b_i$  and  $a_i$  are the filter parameters,  $x(k)$  and  $y(k)$  are the input and the output of the filter,  $k$  is an index corresponding to the "present" time sampling and  $(k-j)$  indicates the value of a variable  $j$  samples earlier.

As an example, the dynamic relation between the input voltage and the output shaft elongation, can be approximated by a delayed second order system with natural frequency of 37.6 radians/s, damping factor of 0.37 and a delay of 30 ms, from data obtained after laboratory experimentation with an actuator and a single segment.<sup>10</sup> The transfer function equation for the linear motor in Laplace form is (2), where  $s$  is the Laplace operator.

$$G(s) = \frac{Y(s)}{X(s)} = \frac{1436.76}{s^2 + 27.824 s + 1413.76} e^{-0.03 s} \quad (2)$$

Sampling this dynamic system with a sampling period of 10 ms using the z-transform of the sampled inverse Laplace transform<sup>7,8</sup>, i.e., using the expression (3),

$$H(z) = (1-z^{-1})Z \left\{ L^{-1} \left( \frac{G(s)}{s} \right) \right\} \quad (3)$$

gives the following pulse transfer function (4), where  $z$  is the z-transform operator.

$$H(z) = \frac{Y(z)}{X(z)} = \frac{0.120528}{z^2 (z^2 - 1.635149z + 0.755677)} \quad (4)$$

The temporal sequence relation derived from (4) is:

$$y(k) = 0.120528 x(k-4) + 1.635149 y(k-1) - 0.755667 y(k-2) \quad (5)$$

Implementing such a sequence requires only three multiplications and two additions. Figure 5 shows the temporal response sequence of the actuator motor from an unitary step input.

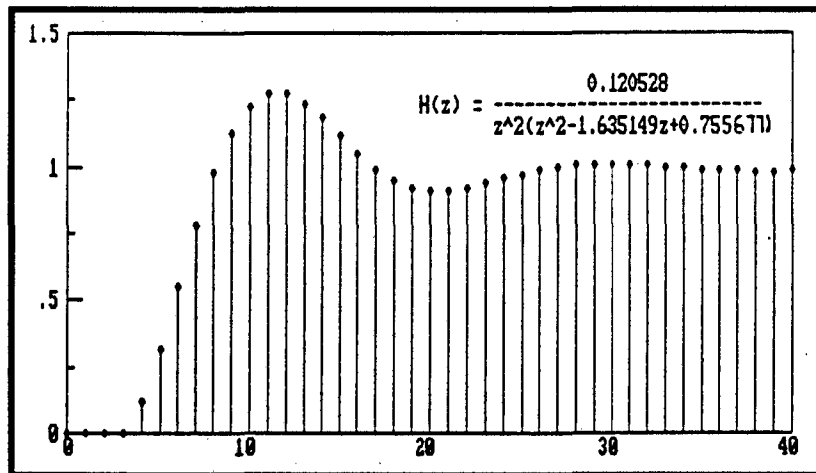


Fig. 5: Discrete temporal response of the actuator motor

#### 4. INTERFACE AND COMMUNICATION

The emulator resides in one of the twelve microcomputers of the multiprocessor control system. The emulator operation is managed through the system's workstation, which communicates to the multiprocessor system by an Ethernet serial link. The system operator can select from his console several emulation conditions, can modify the dynamic models of the different blocks, and can enter in emulation mode from operator commands.

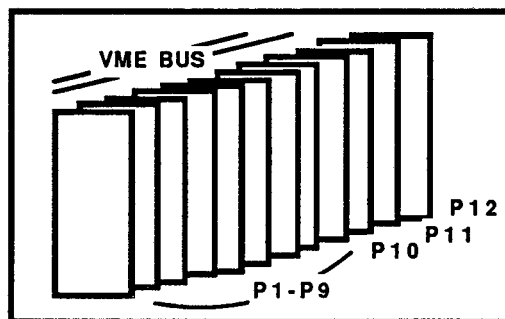


Fig. 6: ACS multiprocessor structure

Once in emulation mode the emulator redirects the actuator control commands generated by the control loop processor (P10) to the emulator processor (P12) instead of sending them to the segment actuators (Fig. 6). The emulator generates the sensor readings in packet form and sends them to the input/output processors (P1-P9) through the VME bus. The execution time of the emulator calculations is much longer than the real-time segment data generation, so in emulation mode the control system real-time clock is frozen to allow for enough time to complete all the calculations. The system runs, therefore, in pseudo-real time, with a time scale determined by the speed of the emulator processor. In the real system the control actuator commands are sent at a 2 Hz rate while the segment data is obtained at a 100 Hz rate. So, the emulator generates a sequence of 50 cycles of sensor readings from each control actuator command cycle.

The principal variables of the emulator are stored in a circular buffer at P11 in an array and can be selectively retrieved at the operator console for analyzing.

## 5. CONCLUSION

This paper has described an emulator for the segmented mirror hardware of the W.M Keck 10m telescope. The emulator has been developed at Lawrence Berkeley Laboratory and will be a valuable tool for evaluating the characteristics and validating the operation of the Segment Alignment Control System (ACS). It is programmed in one of the processors of the multiprocessor control system and emulates the interaction between the mirror system and the control system. The operation of the emulator consists in the redirection of the actuator commands to the emulator processor instead of the mirror hardware and the generation of sensor data to feed the input processors. Realistic models are introduced for each of the emulated parts, and perturbation models can be generated to test the dynamic properties of the ACS. Proper selection of the parameters of the model and of the mirror simulation conditions allow the test of different aspects of the control programs. The emulator is parametrized and accurate models can be adjusted as new real data from the mountain site physical structure are accessible.

## 6. ACKNOWLEDGMENTS

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