Control Technology Test Bed for Large Segmented Reflectors

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ABSTRACT: This paper describes an experimental test apparatus for active control of a seven-segment primary reflector (mirror). Segmented reflectors require an active segment-alignment control system to give the reflecting surface the optical performance of a single-piece reflector. The experimental apparatus, called the Advanced Structures/Controls Integrated Experiment, consists of a Cassegrain optical configuration with a 2-m, seven-segment actively controlled primary mirror supported by a light, flexible truss structure. The test bed is a response to the need for experiments that can simulate the complex dynamic behavior of a large structure and address the myriad of problems associated with precision control of optical surfaces. The paper describes the test bed, presents details of the control and optical measurement systems, and reports on preliminary performance results.

Introduction

Because state-of-the-art focal-plane sensors have become extremely efficient, further improvements in performance for astronomical optical systems must come from the use of large-aperture optics. By increasing the size of the aperture, photon collection capability and/or image quality is enhanced substantially. A number of ground-based optical systems with apertures in the 7-12-m range, such as the Keck Ten-Meter Telescope, are already under design or construction [1], [2]. The ability to launch large, complex payloads, combined with the requirements for improved sensitivity and image quality, has stimulated the design of large-aperture spaceborne optical systems such as NASA’s planned Large Deployable Reflector [3].

In order to make a reflecting surface constructed from a mosaic of segments emulate the optical performance of a single piece of glass, the segments must be oriented individually and positioned with a high degree of accuracy. In a segmented reflector, unlike a monolithic mirror, the mechanical rigidity and geometric accuracy are supplied solely by the support structure. Imperfections in the manufacturing process, deformations due to gravity loads, thermal gradients, attitude dynamics, and structural vibrations make it imperative that the positions of the segments be controlled actively. Therefore, a special segment-alignment control system is required to position the segments precisely so that their combined surfaces can act as a uniform paraboloid.

The two most difficult problems associated with the active control of a large segmented mirror are the complexity of the implementation of the control algorithm and the interaction between the control system actuators and sensors with the dynamics of the support structure. For example, the Keck Ten-Meter Telescope requires 162 sensors, 108 actuators, and a dedicated computer to implement the control system that aligns its 36 segments. In addition, an analytical study of the telescope that modeled the full structure, actuator and sensor set, and control system operation showed that control system stability was seriously affected by dynamic coupling between the segments through the support structure [4]. Tests performed on a single segment and support cell failed to predict this phenomenon because the tests did not account for the effects of collective motion and coupling in the full system [5].

A control-systems-oriented test bed called the Advanced Structures/Controls Integrated Experiment (ASClE) has been developed at the Lockheed Palo Alto Research Laboratory to perform meaningful laboratory experiments for the design, implementation, and validation of control systems for large segmented telescopes. The test bed consists of a 2-m, seven-segment, actively controlled primary mirror supported by a light, flexible truss structure. The optical system emulates that of an f/1.25 Cassegrain telescope and utilizes an actively controlled secondary mirror. The six peripheral segments are controlled in three degrees of freedom using specially developed precision actuators [6].

The segments are aligned by using edge sensors connected to a high-performance array processor that generates the commands for the actuators. A unique feature of the test bed is its optical scoring and calibration system, which eliminates the requirement that the segments have real optical surfaces. Small optical flats, combined with a special faceted secondary mirror, reflect laser beams onto an array of linear position-sensing photodetectors, so that an independent measurement of the tilt motions of each of the active segments can be made.

The test bed was conceived to bridge the gap between the highly sophisticated paper designs for large optical systems and the relative lack of experimental data supporting the validity and feasibility of these new concepts; thus, the prime objective is to provide an experimental tool to develop and validate the new technologies needed to design and build active control systems for large, flexible, segmented optical systems. These technologies include segment-alignment control, figure sensing, structural control, controls/structures interactions, pointing/slewing, image motion stabilization, secondary mirror scanning/chopping, actuator and sensor technology, and digital implementation.

To integrate this wide array of disciplines and technologies, the ASCIE test bed must emulate all essential features of a generic telescopic system. It must have an active segmented primary mirror and an active secondary mirror and exhibit the dynamic behavior of a lightweight flexible structure. In addition, it must provide performance levels commensurate with a real optical system, because the problems associated with nanometer-level and subarcsecond measurement and control are substantially different from those that have been addressed so far in related large-structure experiments.

The near-term goal for the test bed is to demonstrate in the laboratory a fully operating segment-alignment control system with a level of performance comparable to that required for a real telescope. Longer term goals include substantial improvements in bandwidth and disturbance rejection through the use of advanced control techniques, an
active secondary mirror to improve image stability and simulate a chopping secondary, and active structural control to minimize the impact of structural vibration on optical performance.

There have been a number of experimental test beds for control of flexible structures reported in the literature (as indicated by the references listed in [7] and the spacecraft emulator in [8]), but this paper represents one of the first reports of a test bed devoted to active structural control of a segmented reflector. The paper describes the ASCIE experimental setup, including details of the optical measurement system, the sensors and actuators, and the implementation of the control algorithm. Results of analytical and preliminary experimental studies that describe the dynamical behavior and optical performance of the system are presented.

**Technical Challenges**

The performance of any optical system is a direct function of the accurate positioning of each of its components. For small and relatively rigid systems, initial alignment usually is achieved by careful manual adjustment and, thereafter, passively maintained by the mechanical rigidity of the optical bench. Typically, large segmented reflectors are characterized by the lack of temporal and spatial mechanical stability of the structure supporting the optical elements. As a result, an active control system is required to maintain alignment of the segments. Designing and implementing such a control system presents technical challenges in three main areas: sensing, actuation, and controls.

**Sensing**

The lack of dimensional stability of the support structure requires the use of sensors that measure the position of the segments with respect to some unique, stable reference rather than with respect to the underlying structure. The method used for the Keck Ten-Meter Telescope [9], [10] and other systems such as NASA’s Large Deployable Reflector is to measure the relative position of each segment with respect to adjacent segments. This is accomplished by position sensors (edge sensors) mounted near the segment edges. A fixed segment or particular set of points is then chosen as a typical reference for the whole system, and the positions of individual segments are obtained by a special algorithm that applies the proper coordinate transformation to the ensemble of sensor signals.

The edge sensors are required to have a number of special features. They must be accurate to a fraction of the wavelength of light, and their measurement range must accommodate the initially large misalignments caused by the support structure. The performance of the sensor system is also very sensitive to the geometry of the location of individual sensors on the panels and to the processing algorithm. In addition, edge sensing is not a complete answer to segment alignment. Because of electronic biases and drifts, as well as the need to provide an absolute basis to phase the segments with respect to each other, the overall figure must be measured optically for initial calibration and system alignment; thus, the development of optical figure sensors is also a critical part of segmented telescope technology.

**Actuation**

The accuracy and dynamic range requirements for segment-alignment actuators are essentially the same as those for the sensors; however, they are more difficult to meet because of other requirements, such as force output, bandwidth, and smoothness of operation. Friction and stiction, for example, can result in uneven motions that can excite vibrations in the structure. Conventional designs have proven to be inadequate, and new design approaches have been necessary to meet the required performance.

**Controls**

Whether edge sensors or optical figure sensors are used, the resulting control system is highly noncolocated, and dynamic coupling between the individual segments and the support structure may cause the segment control system to become unstable at relatively low bandwidths. The action of one actuator influences the entire reflector and can be sensed by all the sensors. This behavior is the fundamental basis of the controls/structure interaction phenomenon in large segmented reflectors and was demonstrated for the first time in an analytical study of the Keck Ten-Meter Telescope.

In addition, active control of the secondary mirror (e.g., for image stabilization) can also induce controls/structures interaction. Even during an open-loop operation such as spatial chopping, the reaction forces and moments resulting from the motion of the secondary mirror are likely to excite the whole telescope through the metering structure, and, thus, affect the control sensors.

The large number of actuators and sensors involved in controlling a large segmented reflector poses an implementation problem. The Keck Ten-Meter Telescope, for example, has 108 actuators and 162 sensors. Computation requirements and system integration are, therefore, substantially more complex than for conventional control systems.

This wide array of technical challenges must be addressed successfully to build the next generation of large optical systems. Until recently, no test bed existed to develop and validate control system concepts for large segmented reflectors in an integrated fashion. This lack of experimental capability has been a major motivation for development. The ASCIE test bed is an interdisciplinary research project to build an operational laboratory device that contains all the technology required for an active segmented optical system and has performance comparable to a real optical system.

**System Description**

**Design Overview**

The ASCIE test bed consists of a 2-m, seven-segment, actively controlled primary mirror supported by a light, flexible truss structure. The optical system emulates that of an f/1.25 Cassegrain telescope. The six peripheral segments are controlled in three degrees of freedom using specially developed actuators. A schematic drawing is shown in Fig. 1, which illustrates the features discussed next.

**Structure**

The test bed has a strong, lightweight truss structure whose structural-dynamic characteristics are representative of a large, flexible spaceborne system. A design of this type requires a careful trade-off between the need for the structure to support itself in the earth gravity laboratory environment and the need to keep the frequency of the first bending mode as low as possible. Thin-wall stainless-steel tubing is employed in a unique geometric configuration to achieve the correct balance between strength and flexibility.

**Segmented Primary Mirror**

The primary mirror is designed to emulate the critical properties of a real segmented mirror. These properties include segmentation geometry, intersegment spacing, segment mass, inertia and stiffness, and optical focal ratio. The seven-segment primary mirror consists of a ring of six actively controlled hexagonal segments surrounding a fixed center segment that acts as a reference.

**Segment Control System**

The baseline-design segment control system is a direct emulation of the controller used for the Keck Ten-Meter Telescope. This straightforward
An integral control law was implemented to obtain baseline performance data on the simplest possible control algorithm, which can then be compared with more sophisticated control laws incorporating modern control techniques.

Figure 2 illustrates the principle of the segment control system. The relative position of each segment with respect to its three adjacent neighbors is provided by a set of 24 edge sensors (four per segment). These inputs are sent to the control algorithm, which uses them to compute the tilt and piston errors for each of the six controlled segments by comparing the sensor inputs with 24 reference values stored in the computer. The control algorithm then transforms the 18 computed piston- and tilt-error values into the corresponding commands to be sent to each of the 18 segment control actuators.

**Optical Scoring System** An optical scoring system has been developed to obtain independent measurements of segment tilt errors. The scoring system provides an independent check on the computed tilt and piston errors derived from the edge sensors.
System Description

Figure 3 is a photograph of the optomechanical hardware in the laboratory. It shows the segmented primary mirror and the secondary mirror mounted on its hexapod support structure. The focal-plane optics and sensors are also visible. The truss support structure, segment position actuators, edge sensors, and central hexbox/support tube are also shown in the figure.

The arrangement of the control hardware is shown in Fig. 4. The optomechanical hardware communicates directly with a set of custom interface electronics that processes the signals from the edge sensors (inputs) as well as the control computer (outputs). An array processor coupled to a high-performance superminicomputer is used to compute the control outputs. The array-processor/host-computer configuration has two important features for such a test bed. First, it can directly access and store all the states of the system, so that data for controller performance analysis can be obtained directly and in real time. Second, the gain matrix, which effectively controls the loop bandwidth of the system, can be changed between processor cycles in a way that is completely transparent to the control loop. Thus, gain and scaling changes can be effected as easily as with analog hardware in which the operator would turn a gain knob.

Control of the experiment, including a display showing the levels of all the sensor outputs and actuator commands in addition to the computed piston and tilt errors for each of the segments, is provided by a personal computer coupled to both the main control computer and the interface electronics.

Optical Scoring System

An optical scoring system has been developed to obtain independent measurements of segment tilt errors. The scoring system uses a laser mounted inside the central tube, which forms the hub of the structure. Surrounding the laser is an array of two-axis proportional photodetectors that act as the "focal plane." The laser beam is directed at the secondary mirror, which splits the beam into six parts, with each subbeam directed at one of the segments.

Because the segments are not real optical surfaces, a small reflecting flat mounted to the segment is required to retroreflect the beam back to the secondary. The six individual beams are then returned to the focal-plane detectors surrounding the laser after a second reflection off the secondary mirror. Figure 5 illustrates the principle of operation of the scoring system and shows how the faceted secondary mirror is used to split simultaneously the outgoing laser beam and re-reflect the incoming return beams. The photograph on the cover shows the laser beam paths on the laboratory hardware. The bright spots on the panels are the locations of the six reference flats.

The motion of the focused laser spots on each of the six detectors provides a direct measurement of the angular motion of the corresponding segment. However, for this measurement to be meaningful, the angular motion of the secondary mirror must be removed. This is accomplished through the use of a seventh photodetector, which can make a direct measurement of the relative motion of the mirror and the focal plane. Figure 6 shows how a small flat at the center of the secondary mirror is used to retroreflect a portion of the outgoing laser beam. A pellicle is used to direct the return beam through a lens assembly onto the seventh photodetector. The lens is required so that only rotational and not translational motion of the secondary will be measured by the photodetector. In addition, because the laser is set to converge at the much longer path length of the scoring system, the lens acts to provide the correct focus for the secondary mirror control beam.
explore control techniques to reduce its impact.

**Segment-Positioning Actuators** The key to the precision control of the primary mirror is the use of high-performance segment-positioning actuators. These actuators are required to have extremely low noise levels, be able to generate substantial forces over a wide mechanical range, and support a segment in an earth gravity field. They must also have a bandwidth sufficient to accommodate the spectra of expected disturbances. In addition, given that there are a total of 18 actuators, thermal and system power considerations require that energy dissipation be minimized.

Because conventional actuators were unable to meet one or more of the performance requirements, a new actuator design was specially developed at Lockheed. Figure 7 is a schematic diagram of this actuator and the electronic control system that drives it. The actuator utilizes a four-bar linkage connected with flex pivots (rather than bearings) so that it will have the required output force while avoiding the problems of stiction and friction. The actuator operates under closed-loop control by measuring the location of the output shaft with an inductive position sensor and comparing the commanded position with the measured position. The position error is then processed by the analog control electronics, and a power amplifier provides the drive current to the moving-magnet actuator.

A separately controlled automatic system is used to provide force offloading. This system uses a special control loop to measure

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**Actively Controlled Secondary Mirror** The secondary mirror is equipped to provide two-axis active beam-steering control. This feature is important for two reasons. First, the optical scoring system relies on the fact that the secondary mirror will not introduce unwanted motion into the measurement beams. Therefore, an active closed-loop control system that uses the laser as a measurement source has been implemented. This system continuously aligns the secondary to the focal plane and removes all relative angular motion between the secondary and the reference.

The second reason that an active secondary is important is that it will allow the study of controls/structures interaction induced by image-motion compensation and spatial chopping. Vibration of the secondary support structure is a typical problem faced by all large optical systems, and the test bed will be able to demonstrate this effect and
the current in the main actuator. A small servomotor, shown as the force-compensation actuator in Fig. 7, is commanded to move a leaf spring, which applies a force to the linkage mechanism of the main actuator. The automatic system drives the small servomotor until the DC portion of the current in the main actuator is essentially zero.

The performance characteristics of the segment-positioning actuator are shown in the Table. Figure 8 shows an operational prototype of the actuator that has had part of the outer case cut away to expose the internal mechanism.

**Edge-Sensor System** The edge-sensor system consists of 24 inductive position sensors (the same type as is employed on the actuators) mounted on the peripheries of the six actively controlled segments. The sensors measure the relative displacements of the edges of adjacent panels. There is no direct measurement of the displacement of an individual segment with respect to the support structure. The figure of the primary mirror is maintained through the measurement and control of the relative positions of the segments with respect to each other. The central segment, which is fixed, acts as the overall line-of-sight reference for the primary. The mounting technique for a typical sensor is shown in Fig. 9. It is important to note that the displacement is not measured at the boundary between two segments but, rather, at a point displaced toward the center of the segment. Figure 9 shows how a paddle is used to obtain the correct sensor/edge offset. This offsetting of the sensor away from the edge is necessary because there is an ambiguity in the set of measurements of edge displacements that would permit the entire primary mirror to fold like the petals of a flower. That is, the petal-folding motion cannot be detected by a set of sensors located exactly at the segments’ edges. The mathematical explanation for this phenomenon is that the measurement matrix that relates segment motion to sensor output has an ill-conditioned pseudoinverse, and, thus, the sensor outputs are insensitive to the petal motion.

**Structural Characteristics**

A 798-degree-of-freedom finite-element model of the ASCIE structure was developed as part of the initial design process. It included detailed models of the actuators, segments, support truss, and central tube. The model was used initially as a design tool to achieve the desired modal frequencies (i.e., frequencies low enough to emulate a large telescope structure such as that of the Keck Ten-Meter Telescope) while maintaining an acceptable gravity sag. The distribution of modal frequencies of the final design is shown in Fig. 10. The first significant mode (i.e., the mode that affects the optical quality of the image) is at about 12 Hz. The close grouping of modes that can be seen in Fig. 10 is typical of large segmented structures and very different from the regular, well-spaced distribution seen in beamlike structures.

The modal grouping phenomenon is also accompanied by the existence of global modes in which the (segmented) surface of the primary mirror behaves as a continuous membrane. These modes are responsible for adverse interactions between controls and structures as well as for image degradation. A computer-animated movie was made using the ray-trace capability of the finite-element program to evaluate the effect of various modes on image quality.

**Preliminary Experimental Results**

The loop on one segment of the fully assembled structure was closed using its three actuators and six edge sensors. The five other segments were restrained by their own actuator/flexure systems, with the local servoloops closed to keep these actuators locked to the support structure. The loop was closed successfully at a bandwidth of 5 Hz, which is below the 12-Hz stability limit predicted by a modal gain analysis. When higher gains (and, therefore, correspondingly higher bandwidths) were tried, instability was observed; however, no quantitative correlation has been attempted yet.

As discussed previously, the control algorithm in the array processor is calculated, and data can be taken at a 200-Hz sampling rate. The experiment was conducted in a typical laboratory environment and produced a measured rms piston error of about 50 nm and rms tilt errors of less than 0.05 arc-sec, a level of performance that satisfies the required accuracies for an optical system.

The recorded time histories of the piston and tilt errors over a 5-sec period (Figs. 11
and 12) show good static stability, with higher frequency errors caused principally by seismic and sensor noise. This behavior can be contrasted with the corresponding motion of the three control actuators seen in Fig. 13. The 300-nm-amplitude motion exhibited by all three actuators is due principally to slowly varying thermal distortion in the support structure that would have affected the alignment of the segments had they been mounted passively. The actuator motions were commanded by the control system so as to maintain at all times the correct alignment of the controlled segment with respect to its neighbors. As a result, the tilt and piston variations essentially were eliminated; however, excitation occurring at frequencies beyond the system bandwidth cannot be compensated for. Increasing the bandwidth will be the goal of future research. The present integral control scheme has fundamental limitations due to interaction with structural dynamics.

Conclusions

This paper has described the Advanced Structures/Controls Integrated Experiment, which is a test bed for the development of technology related to the control of large, segmented optical systems. The complex structural-dynamics characteristics of large, flexible structures combine with a segment-alignment control system whose performance meets the requirements of an astronomical-quality optical system. The test bed is a unique research tool for assessing and validating a wide variety of control design methodologies, special components such as sensors and actuators, and hardware/software implementations for the control of segmented reflectors. Preliminary experiments have demonstrated a level of performance equal to that required of the segment-alignment control system for the Keck Ten-Meter Telescope. This result is an important step toward satisfying a primary objective of this research—to obtain results traceable to actual systems.

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References

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