Segmented Mirror Active Control System Calibration Postprint

Authors: Wang Bin, Dai Yichun, Xu Fangyu, Jin Zhenyu, Yang Dehua

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Abstract

Active control of segmented primary mirrors constitutes one of the principal challenges in segmented mirror technology. The control performance of the active optics system for the 8-meter ring-segmented solar telescope is predominantly determined by the precision of tilt detection and the accuracy of control model establishment. In the development of an active control system, calibration of tilt detection precision and the establishment of a relatively accurate control model are necessitated—that is, calibration of the active control system itself. Within the experimental system, a Shack-Hartmann wavefront sensor was deployed for real-time detection of segmented sub-mirror tilt, and its repeatability measurement precision was calibrated to achieve an accuracy of 0.014arcsec, which approaches the surface shape control requirements of the 8mRST. Subsequently, utilizing edge sensors and the Shack-Hartmann wavefront sensor, the control matrix of the two-mirror active control system was measured, thereby establishing a relatively accurate control model.

Full Text

Calibration of the Active Control System for Segmented Mirrors

Wang Bin[1],[2], Dai Yichun[1], Xu Fangyu[1], Jin Zhenyu[1], Yang Dehua[3]

[1]Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Abstract: Active control of segmented primary mirrors represents one of the key technical challenges in segmented mirror technology. The control performance of the active optics system for the 8-meter Ring Solar Telescope (8m RST) depends primarily on the accuracy of tip/tilt detection and the precision of the control model. During the development of an active control system, it is essential to calibrate the tip/tilt detection accuracy and establish a sufficiently accurate control model—in other words, to calibrate the entire active control system. In our experimental system, we have implemented a Shack-Hartmann wavefront sensor for real-time detection of segment tip/tilt and calibrated its repeatability to an accuracy of 0.014 arcseconds, which approaches the surface control requirements for the 8m RST. Subsequently, we measured the control matrix of the two-segment active control system using both edge sensors and the Shack-Hartmann wavefront sensor, thereby establishing a more accurate control model.

Keywords: Segmented mirror; Active control; Shack-Hartmann wavefront sensor

1. Introduction to the Two-Segment Active Optics System

As shown in [Figure 1: see original paper], the two-segment active optics system employs a spherical mirror composed of two semi-circular segments, each 300 mm in diameter with an edge thickness of approximately 40 mm. The mirror has a radius of curvature of 2000 mm. One segment remains fixed (referred to as the fixed segment), while the other undergoes active displacement in three degrees of freedom (piston, tip/tilt), designated as the active segment. The entire system is mounted on an optical bench with a horizontal optical axis.

The actuation system consists of three displacement actuators positioned in an isosceles triangle configuration on the back of the active segment. Each actuator is fixed at one end to the base and connected at the other end to the active segment’ s cell. The actuators generate axial displacements to control the three degrees of freedom (piston, tip/tilt) with a travel range of ±5 mm and a resolution of 5 nm.

The measurement system comprises two components: (1) Edge sensors for measuring segment edge height differences. We utilize single-pole capacitive displacement sensors from Physik Instrumente (PI) Germany (model D-E30.100 sensors with E-E12.009 modular digital chassis and central processing unit), offering a dynamic range of ±100 m and a dynamic resolution of 2 nm. These are installed at the segment boundaries. (2) A Shack-Hartmann (S-H) measurement system for segment tilt detection. The core components are a microlens array and CCD, with the optical layout shown in Figure 2: see original paper. The system employs a 5×5 microlens array at the exit pupil, as illustrated in Figure 2: see original paper. The boundary between the two segments aligns with the central column of sub-apertures. The two left columns detect the fixed segment’ s tilt, while the two right columns detect the active segment’ s tilt. The central column can be used for piston detection between segments. summarizes the basic parameters of the S-H tilt measurement system.

2. Calibration of S-H Tilt Measurement System Accuracy

In the two-segment active control system, calibrating the S-H detector’ s tilt measurement accuracy provides a critical basis for evaluating the feasibility of active control, the ultimate surface control precision, and the development of high-precision real-time tilt detection. This calibration also forms the foundation for establishing an accurate control model. A primary challenge in calibrating the S-H system is determining the “known aberration” or reference quantity. We define tilt about the Y-axis as tiltX and tilt about the X-axis as tiltY. Since two edge sensors are installed along the segment boundary, when the segment exhibits tiltY, the difference between the two edge sensor readings changes. Given the high dynamic resolution of these sensors, we can use this differential reading as a reference standard to calibrate the S-H tilt measurements.

To verify calibration accuracy, we introduced a Twyman-Green 4D interferometer (PhaseCam@6000 with measurement precision of 0.00012 at =632.8 nm) upstream of the S-H measurement path’ s beam splitter, as shown in Figure 2: see original paper. A flat mirror enables switching between the 4D interferometer and S-H detector. We employed cross-calibration to characterize the S-H tilt detection linearity and repeatability. Since the edge sensors only respond to tiltY changes, and the S-H detection algorithm is identical for both axes, we can extrapolate the tiltX measurement accuracy from the tiltY calibration results.

The cross-calibration procedure involved moving the displacement actuators in discrete steps to vary the segment’ s tiltY, recording the edge sensor differential reading as the reference standard, and simultaneously measuring the tilt with both the 4D interferometer and S-H detector. To mitigate atmospheric turbulence and local temperature effects, the 4D interferometer integrated 32 measurement frames while the S-H detector integrated 50 frames. [Figure 3: see original paper] shows the correlation between edge sensor differential readings and 4D interferometer tiltY measurements across ten consecutive tiltY variations, while [Figure 4: see original paper] displays the corresponding relationship with S-H detector measurements. We performed least-squares fitting on this data using equation (1):

$$f(x) = p_1 x + p_2$$

The fitting parameters for [Figure 3: see original paper] are: p = 0.000804 arcsec/nm, p = -0.0103 arcsec, with a root-mean-square error (RMSE) of 0.01346 arcsec. For [Figure 4: see original paper]: p = 0.0008067 arcsec/nm, p = -0.00927 arcsec, RMSE = 0.01697 arcsec.

We collected eight independent datasets, performing linear fitting on each. The mean and standard deviation of the fitting parameters across all datasets are presented in and . The results demonstrate excellent repeatability and linearity for the S-H measurements, closely matching the 4D interferometer results. Under our experimental conditions, the S-H repeatability reached 0.014 arcsec, which is compatible with the actuator execution precision of the two-segment system.

3.1 Theoretical Active Control Model

Within the linear range of sensors and actuators, the two-segment active control model can be expressed by equation (2):

$$y = Ax + n$$

where y is the measurement vector comprising edge sensor readings and tilt sensor measurements, x represents actuator displacements, n denotes measurement noise, and matrix A is the control matrix that describes the geometric relationship between actuators and sensors.

[Figure 5: see original paper] illustrates the geometric arrangement of actuators and edge sensors on the segment. When actuator M1 displaces by Δm_1, the entire segment rotates about the axis connecting actuators M2 and M3. The change in each edge sensor reading is given by:

$$\Delta s = \frac{r}{h}\Delta m$$

where r is the perpendicular distance from the edge sensor to the rotation axis, and h is the perpendicular distance from the actuator to the rotation axis. Based on this relationship, we can express the change in each edge sensor as a function of actuator displacements:

$$\begin{cases} \Delta s_1 = h_{11}\Delta m_1 + h_{12}\Delta m_2 + h_{13}\Delta m_3 \\ \Delta s_2 = h_{21}\Delta m_1 + h_{22}\Delta m_2 + h_{23}\Delta m_3 \end{cases}$$

The segment' s tip/tilt changes about the Y and X axes can be expressed in terms of actuator displacements as:

$$\text{tiltX} = \frac{\Delta m_1 - \Delta m_2 + \Delta m_3}{d}$$

$$\text{tiltY} = \frac{\Delta m_1 - \Delta m_3}{d}$$

To integrate these with edge sensing, we convert equations (6) and (7) into equivalent edge height changes using conversion coefficients a_{tx}, a_{ty} such that $\Delta s_{tx} = a_{tx}\text{tiltX}$ and $\Delta s_{ty} = a_{ty}\text{tiltY}$. The complete active control model becomes:

$$\begin{pmatrix} \Delta s_1 \\ \Delta s_2 \\ \Delta s_{tx} \\ \Delta s_{ty} \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ a_{tx} & -a_{tx} & a_{tx} \\ a_{ty} & 0 & -a_{ty} \end{pmatrix} \begin{pmatrix} \Delta m_1 \\ \Delta m_2 \\ \Delta m_3 \end{pmatrix}$$

Using the design specifications, the theoretical control matrix for the two-segment system is calculated as:

$$A_{\text{theory}} = \begin{pmatrix} 1.5281 & -0.64 & 0.0995 \\ -0.6811 & 1.5404 & -0.64 \\ 1.36 & -0.6811 & 1.5404 \\ 0.6811 & -0.0995 & -0.6811 \end{pmatrix}$$

3.2 Measured Active Control Model

We calibrated the actual control matrix A by measuring the real response of edge sensors and the tilt sensor to actuator displacements. Based on the first two rows of equation (8), we determined the response coefficients from actuator commands and measured edge sensor changes. The measurement procedure involved: fixing actuators M2 and M3 while moving M1 in 10 steps, recording the changes in edge sensors 1 and 2, and repeating this 25 times. The same procedure was then performed for M2 and M3 individually. The mean and standard deviation of edge height changes caused by actuator displacements are shown in .

Using the last two rows of equation (8), we determined the tilt response conversion coefficients from actuator commands and measured segment tilt. The measurement method involved: fixing M1 and M3 while moving M2 in 20 steps, recording the S-H detector’ s tiltX measurements, and repeating 45 times. Then, with M2 fixed, we moved M1 and M3 in opposite 20-step increments while recording tiltY measurements, also repeated 45 times. The mean and standard deviation of tiltX and tiltY measurements are presented in .

The resulting measured control matrix is:

$$A_{\text{measured}} = \begin{pmatrix} 1.5703 & -0.5606 & 0.1042 \\ -0.7083 & 1.5732 & -0.6026 \\ 1.4167 & -0.7083 & 1.4946 \\ 0.7083 & -0.1146 & -0.4946 \end{pmatrix}$$

The measured control matrix shows significant deviations from the theoretical matrix, with maximum discrepancies reaching 14.16%. In the theoretical design, actuators M1 and M3 are symmetrically positioned about the semi-circular segment, and the two edge sensors are also symmetrically installed at the segment boundary. Consequently, opposite displacements of M1 and M3 should produce equal but opposite changes in the two edge sensors. However, measurements consistently show that edge sensor 1 exhibits smaller changes than edge sensor 2. This indicates the presence of installation errors between actuators and edge sensors, which, combined with actuator execution errors, cause deviations in the actual sensor responses and tilt conversion coefficients from their theoretical values, ultimately leading to discrepancies in the control matrix.

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4. Discussion and Conclusion

This study calibrated the linearity and repeatability of the S-H tilt detector in the two-segment system using a 4D interferometer and edge sensors, achieving a repeatability of 0.014 arcsec. This precision approaches the surface control requirements for diffraction-limited imaging at 1-micron wavelength for the 8m RST. However, this measurement accuracy was obtained under relatively stable laboratory atmospheric conditions. Further experiments are needed to verify tilt measurement precision under significant turbulence effects. The cross-calibration methodology described herein can be applied to calibrate S-H tilt detection and other tilt measurement schemes under various implementation conditions.

We measured the control matrix of the two-segment active control system using edge sensors and the S-H detector. Installation errors between actuators and sensors resulted in noticeable differences between the measured and theoretical control matrices. Future work will investigate how these matrix discrepancies affect active control performance through closed-loop experiments, thereby establishing tolerance requirements for actuator and sensor installation errors. The calibration procedures described here primarily address quasi-static control matrix errors arising from sensor and actuator installation misalignments. Periodic in-situ calibration of the control matrix represents a potential solution for addressing random control matrix errors, which will be explored in subsequent research.

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Note: Figure translations are in progress. See original paper for figures.