

Postprint of Research on Pose Adjustment Methods for Sub-mirrors in Two-mirror Segmented Active Optics

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Abstract

A two-mirror system is established to simulate the relative pose relationships among individual sub-mirrors in a segmented mirror. A pose detection method is proposed that combines edge sensors installed on adjacent sub-mirror edges with tilt sensors to detect three degrees of freedom of sub-mirror tilt (tip/tilt) and axial translation (piston). Active correction experiments are conducted using both theoretical and measured control matrices. Experimental results demonstrate that when correcting with the theoretical control matrix, the edge sensor RMS error is not greater than 7.3 nm, and the tilt RMS error is not greater than 0.076 arcseconds; when correcting with the measured control matrix, the edge sensor RMS error is not greater than 7.4 nm, and the tilt RMS error is not greater than 0.080 arcseconds. The work presented herein can provide a reference solution for addressing the problem of insufficient detection of relative positional degrees of freedom between sub-mirrors in annular segmented active optics.

Full Text

Research on Adjustment Method of Segment Pose in a Two-Mirror Active Optics System

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Abstract

A two-mirror active optics system is established to simulate the relative pose relationship between adjacent segments. We propose a pose detection method that combines edge sensors mounted on adjacent segment edges with a tilt sensor to detect three Degrees of Freedom (DOFs): tip/tilt and piston. Active correction experiments are conducted using both theoretical and measured control matrices. The results demonstrate that when using the theoretical control matrix, the Root Mean Square (RMS) error of edge sensors is no greater than 7.3 nm, and the tilt RMS error is no greater than 0.076 arcseconds. When using the measured control matrix, the edge sensor RMS error is no greater than 7.4 nm, and the tilt RMS error is no greater than 0.080 arcseconds. This work provides a reference solution for the problem of insufficient detection of relative position DOFs between segments in ring-type segmented active optics.

Keywords: Segmented mirror active optics; Sensor; Pose detection; Active control

The Chinese Giant Solar Telescope (CSGT) plans to employ ring-type segmented mirror active optics technology to achieve an 8-meter ring-shaped primary mirror, consisting of 24 segments forming a ring with a diameter of 8 m and width of 1 m [1]. Unlike existing large telescopes such as the Keck telescope [2] that use hexagonal segments in a “locking” configuration to determine relative positions—requiring only edge sensors to monitor piston errors between segments—CSGT’s ring-type design faces insufficient DOF detection if relying solely on edge sensors, making active maintenance impossible [3]. Therefore, additional tilt sensors are necessary to detect all three DOFs of segment pose: piston, tip, and tilt [4]. Edge sensors measure height differences between segment edges, while tilt sensors detect changes in segment inclination, enabling calculation of position variations. Compensation is then applied through displacement actuators on the back of each segment. The critical element for maintaining relative positions between primary mirror segments is the active control system design [5-6]. To validate this approach, a two-mirror segmented active optics system is constructed, where one segment remains fixed while the other undergoes active displacement in three DOFs to simulate typical pose variations in a segmented primary mirror.

1 Introduction to the Two-Mirror Segmented Active Optics System

The two-mirror segmented active optics system simulates the characteristics of an 8 m ring-type segmented optical system, capturing its key features and reflecting the core research content. As shown in [Figure 1: see original paper], the system primarily comprises two identical semicircular segments, segment support/positioning mechanisms, displacement actuators, safety protection mea-

tures, and a base. Each semicircular segment has a diameter of 300 mm, edge thickness of 40 mm, gap of approximately 2 mm, and weight of 3.2 kg. The mirror substrate is Zerodur glass-ceramic, with both reflective surfaces supported at three points and surface figure error of approximately 5.2 nm. One segment is fixed (called the fixed segment), while the other undergoes active displacement in three DOFs (called the active segment). The active segment's precise adjustments are achieved through displacement actuators.

Displacement actuators regulate out-of-plane displacement through length variations [7]. According to segmented mirror operation principles, each segment requires three displacement actuators for support and pose adjustment to achieve three-DOF precision motion. The actuators used in this system offer large stroke, high load capacity, high precision (10 nm resolution), low power consumption, and minimal airflow disturbance [8].

2.1 Segment Axial Displacement (Piston) Detection

Conventional displacement sensors are installed at segment edges, hence called edge sensors. For full-aperture segmented mirrors, the “locking” function between segments means edge sensor measurements alone suffice to determine relative positions. However, this approach has drawbacks: if an edge sensor fails, replacement and maintenance become extremely complex. For ring-type aperture segmented surfaces without “locking” functionality, edge sensors are installed on the experimental prototype to detect height differences between segment edges, as shown in [Figure 2: see original paper]. This experimental system employs PI D-E30 single-stage capacitive displacement sensors with a dynamic range of 50 m and resolution of approximately 2 nm.

2.2 Segment Tilt (Tip/Tilt) Detection

Tilt measurement employs a digital camera-based laser angle measurement method. The tilt system consists of a computer, laser, and lensless digital camera. The principle of the digital camera laser angle measurement system is shown in [Figure 3: see original paper]. The digital camera connects to the computer via USB, while the laser is vertically fixed to the optical mirror and aligned with the camera. Due to the laser beam's excellent collimation, the output can be considered parallel [9]. The laser beam directly reaches the digital camera, which captures spot images before and after rotation. The computer calculates spot displacement on the camera target to determine the tilt angle of the experimental prototype. Spot positions on the target coordinate system are shown in [Figure 4: see original paper].

Let A_0 and A_1 represent spot coordinates on the camera target before and after movement. If the active mirror rotates about the x-axis by tip angle θ_x , causing spot displacement y_s along the y-axis, and rotates about the y-axis by tilt angle θ_y , causing spot displacement x_s along the x-axis, with L being the distance between laser and camera, their relationship is:

$$\tan(\theta_x) = \frac{y_s}{L}, \quad \tan(\theta_y) = \frac{x_s}{L}$$

The experimental system uses a digital camera with 752 (H) \times 480 (V) pixels and 6 m \times 6 m pixel size. A 650 nm red laser is fixed to the active mirror housing to reflect tip/tilt changes, positioned 1725 mm from the camera, as shown in [Figure 5: see original paper].

3.1 Theoretical Control Matrix

The control matrix is determined by the relative geometry between sensors and actuators. Analyzing the geometric relationships between displacement actuators, displacement sensors, and tilt sensors yields the theoretical control matrix. [Figure 6: see original paper] shows the layout of displacement actuators and sensors. Referring to [Figure 6: see original paper], D1, D2, and D3 denote actuator positions arranged in an isosceles triangle; P1 and P2 denote edge sensor positions in symmetric distribution; point a indicates the laser mounted vertically on the segment edge.

Let d_1, d_2, d_3 be actuator displacements; d_0 be the active mirror' s axial translation; and the active mirror' s relative dihedral and interleaved tilt angles be represented by appropriate variables. The transformation from actuator displacements to the three DOFs can be expressed as:

$$\begin{bmatrix} d_0 \\ \theta_x \\ \theta_y \end{bmatrix} = A \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

where A represents the transformation matrix based on the isosceles triangle geometry.

Let h be the height and b the base of the actuator triangle. Let Q be the triangle' s centroid, with l_1, l_2, m_1 , and m_2 representing the vertical and horizontal distances from Q to P1 and P2, respectively. The three DOF variations can be expressed in terms of sensor measurements. Let e_1, e_2 be edge sensor measurements and θ_x, θ_y be tilt sensor measurements:

$$\begin{bmatrix} e_1 \\ e_2 \\ \theta_x \\ \theta_y \end{bmatrix} = B \begin{bmatrix} d_0 \\ \theta_x \\ \theta_y \end{bmatrix}$$

Substituting the previous equation yields the complete sensor response:

$$\begin{bmatrix} e_1 \\ e_2 \\ \theta_x \\ \theta_y \end{bmatrix} = BA \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

Since θ_y can be obtained from both edge and tilt sensors, the matrix exhibits linear dependence. The control system uses edge sensor and digital camera laser tilt measurements to control actuator displacements. For unit consistency, we define $\theta_x = \frac{m_x}{L}$ and $\theta_y = \frac{m_y}{L}$, where m_x and m_y are spot displacements on the camera target. The theoretical design dimensions are: $l_1 = l_2 = 73$ mm; $m_1 = m_2 = 34$ mm; $h = 75$ mm; $b = 86$ mm. Substituting these into the matrix equation and solving for the generalized inverse yields the 3×3 theoretical control matrix:

$$C_{\text{theoretical}} = \begin{bmatrix} -1.56 & 13.84 & -0.075 \\ -1.56 & -13.84 & -0.075 \\ 2.12 & 0 & 0.15 \end{bmatrix}$$

3.2 Measured Control Matrix

The measured control matrix is obtained experimentally by actuating each actuator individually and recording sensor responses. Running actuator #1 alone for 20 steps (5 nm per step) while recording measurements yields the first column of the transfer matrix. [Figure 7: see original paper] shows the fitted experimental curve versus theoretical design for actuator #1. The fitted slope for edge sensor P1 is -1.562, and for tilt θ_x is -0.075. Similarly, the remaining slopes from edge sensor P2 and the CCD are 13.84 and 12.71, forming the first column. Repeating this process for the other two actuators yields the complete transfer matrix:

$$T = \begin{bmatrix} -1.562 & -1.558 & 2.120 \\ 13.84 & -13.82 & 0.003 \\ -0.075 & -0.074 & 0.149 \end{bmatrix}$$

After correction to a 3×3 square matrix and inversion, the measured control matrix becomes:

$$C_{\text{measured}} = \begin{bmatrix} -0.321 & 0.036 & -0.161 \\ -0.321 & -0.036 & -0.161 \\ 0.472 & 0 & 0.322 \end{bmatrix}$$

The discrepancy between theoretical and measured control matrices arises from: (1) equipment alignment errors during optical platform setup, causing geometric position errors; and (2) potential step loss during actuator operation.

4.1 Experimental Correction Using Theoretical Control Matrix

To validate the theoretical control matrix performance, experiments were conducted in a static environment with closed-loop active correction every 5 seconds for 25 minutes. [Figure 8: see original paper] shows the time evolution of edge sensors P1 and P2, and digital camera tilt measurements. Uncorrected edge sensors exhibit divergent trends over time, while corrected sensors converge within a limited range. Tilt θ_x correction is less pronounced, whereas θ_y correction is significant. Table 1 provides RMS errors: edge sensor RMS error ≤ 7.4 nm, digital camera tilt measurement RMS error ≤ 0.080 arcseconds, meeting control requirements and demonstrating system stability.

4.2 Experimental Correction Using Measured Control Matrix

Similar experiments using the measured control matrix were performed under identical conditions. [Figure 9: see original paper] shows the corresponding time evolution curves. The results mirror those of the theoretical matrix: uncorrected edge sensors diverge while corrected ones converge. Table 2 indicates edge sensor RMS error ≤ 7.3 nm and tilt measurement RMS error ≤ 0.05 arcseconds, satisfying control requirements and confirming system stability.

Conclusion

This paper addresses the problem of insufficient DOF detection for relative positioning between segments in giant telescopes with ring-type segmented mirrors. By constructing a two-mirror experimental system, we derived both theoretical and measured control matrices and performed active correction experiments on simulated segment displacements. The results demonstrate that both matrices effectively correct displacement errors between adjacent segments. With the theoretical control matrix, edge sensor RMS error ≤ 7.4 nm and tilt measurement RMS error ≤ 0.080 arcseconds. With the measured control matrix, edge sensor RMS error ≤ 7.3 nm and tilt measurement RMS error ≤ 0.05 arcseconds. Both satisfy the error control requirements of the two-mirror experimental system, providing a reference solution for segment pose adjustment in the 8 m ring-type solar telescope.

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

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