Design and Cryogenic Performance of a Hexapod Platform for a Large Ground-based Wide Field Survey Telescope (Postprint)

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Abstract

The thermal gradient is an important factor that causes degradation to the image quality of telescopes. In order to ensure the accurate alignment of the primary focus unit and the primary mirror, the hexapod platform (as a corrector) is investigated in this paper. First, a ground-based telescope with 2.5 m aperture and 3.5 deg field of view is described. The telescope is under construction, and it is expected to be finished in 2023. Second, the hexapod platform with flexure hinges utilized to adjust the primary focus unit is proposed, which is applied as a corrector. Then, the inverse kinematics of the platform is established and an open-loop control system is built based on it. Finally, the cryogenic performance test for the hexapod platform is performed. The experimental results show that the resolution and repeatability of the translation for the hexapod platform can be achieved at the micrometer level. The resolution and repeatability of the rotation can be achieved at the arc-second level. Therefore, the cryogenic performance of the hexapod platform can meet the optical imaging requirements of the wide-field ground-based telescope. The kinematic analysis and cryogenic performance tests in the paper provide a technical reference for the precise alignment of the primary focus unit and the primary mirror, which can improve the imaging quality of the telescope.

Full Text

Preamble

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Design and Cryogenic Performance of a Hexapod Platform for a Large Ground-based Wide Field Survey Telescope

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Abstract

Thermal gradients are a critical factor causing degradation in telescope image quality. To ensure accurate alignment between the primary focus unit and the primary mirror, this paper investigates a hexapod platform serving as a corrector. First, we describe a ground-based telescope with a 2.5 m aperture and 3.5° field of view currently under construction and expected to be completed in 2023. Second, we propose a hexapod platform utilizing flexure hinges to adjust the primary focus unit, applied as a corrector. The inverse kinematics of the platform is then established, and an open-loop control system is built based on this model. Finally, cryogenic performance testing of the hexapod platform is performed. Experimental results demonstrate that the resolution and repeatability of translation for the hexapod platform achieve micrometer-level precision, while rotation resolution and repeatability reach arc-second-level precision. Therefore, the cryogenic performance of the hexapod platform meets the optical imaging requirements for wide-field ground-based telescopes. The kinematic analysis and cryogenic performance tests presented in this paper provide a technical reference for precise alignment between the primary focus unit and primary mirror, which can improve telescope imaging quality.

Key words: methods: miscellaneous –space vehicles: instruments –telescopes –miscellaneous

1. Introduction

The image quality of an astronomical telescope is affected by the alignment between the secondary mirror and primary mirror. However, due to gravity, wind vibration, and temperature variations, the secondary mirror may become misaligned (Pottebaum & MacMynowski 2006; MacMynowski & Andersen 2010;

Angeli et al. 2011; Irarrazaval et al. 2014; MacMartin & Vogiatzis 2014). To accurately align the secondary mirror within six degrees of freedom (DOF) relative to the primary mirror, most telescopes employ a high-precision adjustment mechanism as an active optical focusing system (Yang et al. 2018; Wang et al. 2023). Additionally, the designed secondary mirror (also referred to as the primary focus unit) can weigh up to 1.2 tons, making a parallel mechanism with high load capacity the most suitable choice. Parallel mechanisms have been widely used in active optical focusing systems, such as the Gran Telescopio Canarias (Casalta et al. 2004), VLT Survey Telescope (Schipani et al. 2007, 2008), and James Webb Space Telescope (Wells et al. 2004; Chonis et al. 2018).

It is worth noting that the effect of varying temperatures on optical imaging quality cannot be ignored. Especially for space telescopes, relevant cryogenic tests are required (Streetman & Kingsbury 2003; Wolf et al. 2018). However, for ground-based telescopes with wide fields of view, the effect of cryogenic temperatures on the active optical focusing system has not been investigated and verified in detail. For example, performance tests for the hexapod platform in the Large Synoptic Survey Telescope were conducted only in room-temperature environments (Neill et al. 2012, 2014; Sneed et al. 2016, 2018). Thus, relevant research remains incomplete. For hexapod platforms used for active focusing, current research is limited to general testing (Cao et al. 2022). Considering that temperature variations directly affect telescope imaging quality and the performance of electronic components, the cryogenic performance of this platform must be verified.

The main contribution of this paper is presenting a high-precision hexapod platform with flexure hinges for the primary focus unit that exhibits excellent cryogenic performance. First, the structural design of the hexapod platform is described in Section 2. The inverse kinematics of the hexapod platform is then established, and the assembly of the primary focus unit and an open-loop control system built based on it are described in Section 3. The performance of the hexapod platform is tested after high-low temperature cycling experiments in Section 4. Finally, conclusions are presented in Section 5.

2. Assembly

The integrated assembly of the astronomical telescope is shown in Figure 1 [Figure 1: see original paper]. The telescope weighs approximately 37 tons and consists mainly of a mount structure, primary mirror, and primary focus unit. The telescope envelope has a cylindrical shape (when the optical axis of the primary focus unit is vertical) with a height and diameter of approximately 4.5 m and 6.5 m, respectively. The telescope' s pose control is driven by a brushless torque motor, allowing the telescope to orient in any direction to cover the area of sky under investigation. The primary mirror can rotate about both a vertical axis (azimuth axis) and a horizontal axis (elevation axis).

The optical configuration of the designed astronomical telescope consists primarily of a Zerodur primary mirror and primary focus unit, as shown in Figure 2 [Figure 2: see original paper]. The Zerodur primary mirror has a 2.5 m aperture and 3.5° field of view. Incident light enters the camera' s focal plane through the primary focus unit, enabling the primary focus unit to function as a corrector. The primary focus unit includes six lenses with diameters ranging from 0.29 to 0.87 m.

During actual astronomical observations, optical alignment between the primary mirror and primary focus unit critically affects telescope image quality. However, at this time, optical alignment is biased by factors such as gravity, wind vibration, and temperature, causing the primary mirror and primary focus unit to deviate from their ideal positions and produce optical misalignment, thereby reducing optical imaging quality. It should be noted that angular deviation of the primary mirror resulting in telescope pointing error can be easily compensated by controlling the azimuth/elevation angle via the torque motor. Optical aberration due to misalignment between the primary mirror and primary focus unit can be compensated by controlling the corrector' s posture. Since the primary focus unit requires no fewer than six degrees of freedom, the hexapod platform is applied as a corrector.

As shown in Figure 3 [Figure 3: see original paper], to facilitate disassembly for maintenance, the primary focus unit is assembled as a single unit on the hexapod platform. The platform' s performance directly impacts the optical alignment between the primary mirror and primary focus unit. Therefore, to maximize optical imaging quality, the hexapod platform' s performance must be explicitly defined, as shown in Table 1 . The working conditions for the hexapod platform are shown in Table 2 .

3. Structure Design

As shown in Figure 4 [Figure 4: see original paper], the primary focus unit is fixed to the hexapod platform, which consists mainly of a moving platform, flexure hinges, actuators, and a fixed base. To avoid contamination of the optical system, the platform must be sealed to prevent lubricant spillage. Hydraulically driven equipment cannot be considered. Additionally, the optical system requires high precision and stability, meaning the platform must have very high precision and stiffness. Therefore, gas-driven technologies cannot be considered either.

As shown in Figure 5 [Figure 5: see original paper], the actuator consists primarily of a brushless torque motor, incremental encoder, planetary roller screw, hall limit switch, harmonic gear drive, and absolute encoder. Compared to planetary ball screws, planetary roller screws offer higher stiffness due to their line contact approach. The active optical system operates in an open loop, requiring high bidirectional repeatability. Since backlash can seriously affect this repeatability, a pre-tightened split-nut arrangement is used to eliminate backlash.

The hexapod platform has a speed limit for optical alignment. The actuator' s output speed relies mainly on a harmonic drive (strain wave) gear drive with a 50:1 reduction ratio, which effectively guarantees accuracy, repeatability, and resolution. Compared to conventional gearboxes, the harmonic gear drive offers advantages of small size, light weight, zero backlash, and excellent positioning accuracy and repeatability.

A DC brushless motor has been selected as the drive element, offering higher efficiency, better reliability, longer life, and more precise motion control compared to DC brushed motors. The fine pitch (1 mm lead) of the roller screw and high gear reduction ratio (50:1) of the harmonic gear drive limit motor torque, allowing the actuator to be self-locking or non-reversible. This measure provides the hexapod platform with power-down holding capability and eliminates the requirement for brakes and their associated heat generation.

The absolute encoder is selected as a non-contact high-performance encoder that achieves functions such as power-down storage and multi-turn counting. Mounted at the output, it accurately records each actuator’ s position at any given time. Even when power is switched off, the actuator position provides equally accurate feedback for closed-loop control when power is restored. An incremental encoder mounted on one end of the motor provides speed feedback. Finally, hall switches act as safety limits.

It is important to note that the rotating joint adopts flexure hinges rather than traditional Hook hinges. These hinges offer advantages of no mechanical clearance, no friction, and no assembly requirements. The application of flexure hinges minimizes lag and improves overall telescope performance. The smoother, lag-free rotation facilitates image stabilization. Based on wide field-of-view requirements, the designed flexure hinge must achieve a rotation angle of no less than 2.5°. As the weakest part of the platform, the flexure hinge’ s axial stiffness directly affects the platform’ s pointing accuracy and loading capacity, while its bending stiffness directly affects the optical system’ s stability.

Based on the above analysis, the axial and bending stiffnesses of the flexure hinge must be no less than 3.00$\times10^{8}$ N · m^{-1} and 1.00$\times10^{3}$ N · m · rad^{-1}, respectively. The hinge material is selected as 17-4 PH stainless steel with an elastic modulus of 196 GPa, Poisson’s ratio of 0.3, and yield strength of 1100–1300 MPa. The designed flexure hinge achieves axial and bending stiffnesses of 3.15$\times10^{8}$ N · m^{-1} and 1.17$\times10^{3}$ N · m · rad^{-1}, respectively. Most importantly, the von Mises stress of the flexure hinge serves as an indicator for evaluating system fatigue life. This hinge’ s von Mises stress is 574 MPa, which is much less than the yield strength. Therefore, the designed flexure hinge can be applied in wide field-of-view optical systems.

4.1. Inverse Kinematic

Currently, control systems for parallel mechanisms are developed primarily based on inverse kinematics. For the hexapod platform with flexure hinges, a simplified inverse kinematics model is built for control system development.

The platform configuration is shown in Figure 6 [Figure 6: see original paper]. The center of rotation for the designed flexure hinge can be approximated as being at its geometric center. A and B are the geometric centers of the upper and lower hinges, respectively. and are the distribution angles of the upper and lower hinges, respectively. h is the height between the upper and lower platforms in the configuration. R and R are the distribution radii of the upper and lower hinges, respectively. Coordinate systems P-XYZ and O-XYZ are fixed in the distribution planes of the upper and lower hinges, respectively. The relevant configuration parameters are specified in Table 3 .

Based on the closed-loop vector relationship, the vectors l (i = 1,2,3···6) for each limb can be expressed as:

$$l = R(\alpha, \beta, \gamma) \cdot P + T - B$$

where the rotation matrix R(α, β, γ) can be expressed as:

$$R = [c\beta \cdot c\gamma, -c\beta \cdot s\gamma, s\beta; s\alpha \cdot s\beta \cdot c\gamma + c\alpha \cdot s\gamma, -s\alpha \cdot s\beta \cdot s\gamma + c\alpha \cdot c\gamma, -s\alpha \cdot c\beta; -c\alpha \cdot s\beta \cdot c\gamma + s\alpha \cdot s\gamma, c\alpha \cdot s\beta \cdot s\gamma + s\alpha \cdot c\gamma, c\alpha \cdot c\beta]$$

where α, β, and γ are the rotation angles of coordinate system P-XYZ relative to O-XYZ about the x, y, and z axes, respectively, and s and c are abbreviated forms of sin and cos, respectively.

At this point, the length l of each limb can be expressed as:

$$l = ||l||$$

In general, the length of each limb depends not only on its own control inputs but also on other limbs. Therefore, the desired length variation ΔL of each limb is referred to as active drive, while the length variation ΔL due to influence from other limbs is referred to as passive drive. The total length variation ΔL of each limb can be expressed as:

$$\Delta L = \Delta L + \Delta L$$

Additionally, the angle of rotation of the screw relative to the nut is Δ , with counterclockwise rotation defined as positive. Therefore, ΔL can be expressed as:

$$\Delta L = (n \cdot S \cdot \Delta)/(2\pi)$$

where n = 1 if the roller screw is left-handed; otherwise, n = 2, and S is the screw lead. This inverse kinematics model has been verified by the rigid-flexible coupling simulation system (Wang et al. 2023).

4.2. The Principle of the Control System

As shown in Figure 7 [Figure 7: see original paper], an open-loop control system is built based on the established inverse kinematics. First, based on optical alignment requirements, the length variation of each limb is calculated using the platform' s desired pose. Next, the motion controller outputs each limb' s length.

A laser displacement sensor then measures the platform’ s performance. Finally, the measured data are analyzed based on the 3σ principle. Absolute encoders make closed-loop position feedback more accurate, while incremental encoders provide velocity feedback to the motor. Since position and velocity feedback are only for these limbs, the hexapod platform’ s control system operates in open loop.

5.1. Cryogenic Test

In general, telescope image quality is affected primarily by wind vibration, gravitational deformation, and temperature. Temperature gradients affect not only image quality but also hexapod platform stability. Temperatures that are too high or too low may affect the performance of electronic components and platform accuracy. Therefore, temperature cycling experiments are required.

It should be noted that the hexapod platform is designed to improve telescope image quality through active optical alignment. Consequently, the platform’ s performance under temperature cycling tests directly reflects actual image quality improvement. Drastic temperature variations occur in harsh operating environments, so the vault must be closed after observation to protect the telescope, though temperature variations still require monitoring.

The test temperature varies approximately between +50°C and −30°C within a 24-hour period. As shown in Figure 8 [Figure 8: see original paper], the hexapod platform is placed in a high-low temperature chamber. According to Table 2 , the platform’ s operating temperature is −30°C to +50°C and storage temperature is −40°C to +70°C, representing a relatively large temperature difference. Based on requirements, the cyclic temperature variation is detailed in Figure 9 [Figure 9: see original paper]. Temperature reduction is achieved by filling with liquid nitrogen, while temperature increase is achieved by electrical heating. It is important to note that nitrogen is required during temperature increase to prevent atomized water droplets, which are harmful to electronic components. During each temperature equilibrium period, a relevant motion experiment is performed on the platform during the last half hour. The total experiment duration is 24 hours, designed to mimic daily temperature variations. It is worth noting that real-time temperature variation control is difficult; therefore, the mimicked temperature variations are only approximately the same as actual variations, though the maximum and minimum temperatures in the experiment exactly match actual conditions.

In electrical circuits, current significantly impacts circuit performance and safety. Proper current is essential for correct operation and extended circuit life, with the ideal maximum current not exceeding 21.3 A. Experimental results show that the maximum current does not exceed 11 A, meeting requirements. Moreover, current increases as temperature decreases because the grease density in the harmonic reducer and screw increases at lower temperatures, leading to increased damping. Therefore, the motor must overcome this grease damping during motion.

5.3. Resolution

To verify the effect of temperature variations on the wide field of view, the hexapod platform' s workspace must be re-estimated. According to Table 1 , translational strokes along the x, y, and z axes are $±$10 mm, $±$10 mm, and $±$15 mm, respectively, while rotational strokes are $±$1.5°, $±$1.5°, and $±$1.0°. As shown in Figure 10 [Figure 10: see original paper], resolution is an inherent characteristic of the hexapod platform, referring to the minimum mechanical step. In the hexapod platform assembly, despite using flexure hinges instead of conventional hinges, mechanical gaps between other components are unavoidable. Additional influencing factors include machining accuracy of the mounting plane, motor and screw resolution, encoder resolution, and screw torque deformation. Higher resolution is essential for high imaging quality.

According to Table 1 , the ideal resolutions for translation and rotation are 0.5 m and 0.6 arcsec, respectively. Test results show that actual resolutions for translation and rotation are 0.5 m and 0.5 arcsec, meeting application requirements, as shown in Figure 11 [Figure 11: see original paper].

5.4. Repeatability

Repeatability is the consistency between actual poses when responding to the same commanded pose multiple times from the same direction. It is an indicator of hexapod platform performance stability. A hexapod platform with high repeatability can achieve optical alignment using open-loop control and is better able to use relevant algorithms to improve accuracy.

According to Table 1 , the ideal repeatability for translation and rotation are $±$3 m and $±$1.5 arcsec, respectively. The experimental small step sizes for translation and rotation are 0.5 mm and 1250 arcsec, as shown in Figure 12 [Figure 12: see original paper]. The large step sizes are 10 mm and 1.5°, as shown in Figure 13 [Figure 13: see original paper]. Experimental results show that actual repeatability for translation and rotation are $±$2.5 m and $±$1.5 arcsec, meeting requirements.

6. Conclusions

This paper briefly describes performance evaluation of the hexapod platform for astronomical telescope optical alignment in a high-low temperature cycling environment. First, the detailed structure of the primary focus unit and hexapod platform for the astronomical telescope is presented. Next, simplified inverse kinematics of the platform is established and an open-loop control system is developed based on it. Then, to consider drastic ambient temperature variation, the hexapod platform is subjected to high-low temperature cycling experiments. Experimental results show that the maximum current does not exceed 11 A, meeting requirements. Finally, the hexapod platform' s performance is tested. Experimental results demonstrate that the workspace meets wide field-of-view requirements. The resolution of translation and rotation are 0.5 m and 0.5 arcsec, respectively, while repeatability of translation and rotation are $±$2.5 m and $±$1.5 arcsec, respectively. Consequently, the designed hexapod platform maintains excellent performance in cryogenic experiments, meeting application requirements.

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References

Angeli, G. Z., Vogiatzis, K., MacMynowski, D., et al. 2011, Proc. SPIE, 8336, 46
Cao, Y., Wang, J., Fan, W., et al. 2022, ApOpt, 61, 3566
Casalta, J. M., Arino, J., Canchado, M., et al. 2004, Proc. SPIE, 5495, 507
Chonis, T. S., Gallagher, B. B., Knight, J. S., et al. 2018, Proc. SPIE, 10698, 1129
Irarrazaval, B., Buleri, C., & Johns, M. 2014, Proc. SPIE, 9150, 725
MacMartin, D. G., & Vogiatzis, K. 2014, Proc. SPIE, 9150, 259
MacMynowski, D. G., & Andersen, T. 2010, ApOpt, 49, 625
Neill, D. R., Gressler, W. J., Sebag, J., et al. 2012, Proc. SPIE, 8444, 169
Neill, D. R., Sneed, R., Dawson, J., Sebag, J., & Gressler, W. 2014, Proc. SPIE, 9151, 772
Pottebaum, T., & MacMynowski, D. G. 2006, JFS, 22, 3
Schipani, P., Ferragina, L., Marty, L., et al. 2007, Proc. SPIE, 6715, 22
Schipani, P., Perrotta, F., Molfese, C., et al. 2008, Proc. SPIE, 7018, 1380
Sneed, R., Neill, D. R., Caldwell, B., et al. 2018, Proc. SPIE, 10700, 1024
Sneed, R., Neill, D. R., Kidney, S., et al. 2016, Proc. SPIE, 9906, 190
Streetman, S., & Kingsbury, L. 2003, Proc. SPIE, 4850, 274
Wang, X., Yu, Y., Xu, Z., et al. 2023, OExpr, 31, 3908
Wells, C., Whitman, T., Hannon, J., & Jensen, A. 2004, Proc. SPIE, 5487,
Wolf, E. M., Gallagher, B. B., Knight, J. S., et al. 2018, Proc. SPIE, 10698,
Yang, D.-H., Cheng, Y., Wu, C.-C., Fei, F., & Jin, Z.-Y. 2018, RAA, 18,

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