Design and Experimental Validation of a Stepper-Motor-Based Displacement Actuator (Postprint)

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Date: 2018-11-19T00:00:00+00:00

Abstract

In the context of ring solar telescope applications, a stepper motor-based displacement actuator has been developed and performance experimental tests have been conducted to obtain its performance indicators. The structural configurations of common large-travel high-precision displacement actuators were analyzed, and the displacement scaling type was selected as the basic structure. This displacement actuator employs a stepper motor integrated with a planetary reducer as the driving element, and utilizes a screw transmission with a special backlash-elimination structure as the displacement scaling mechanism, in order to realize a design featuring high resolution, high stiffness, and high precision. Performance experimental tests of the displacement actuator were carried out, and the results indicate that: the axial displacement range of this displacement actuator is \$±\$2mm, it can achieve a step resolution of 1 m under different loads, and the closed-loop output accuracy of displacement is better than 1 m. The developed displacement actuator provides important technical support for the construction of the ring solar telescope, and can serve as a reference for engineering applications of other precision optical mirror support systems.

Full Text

Preamble

Development and Test of a Stepper Motor Driven Displacement Actuator

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Abstract

A displacement actuator driven by a stepper motor was developed for a ring solar telescope, and comprehensive performance tests were conducted to evaluate its characteristics. Three common structural configurations for large-stroke, high-precision displacement actuators were analyzed, and the displacement scaling type was selected as the basic architecture. The actuator employs a stepper motor integrated with a planetary reducer as the driving element, utilizing a specially designed backlash-elimination screw transmission as the displacement scaling mechanism to achieve high resolution, high stiffness, and high precision. Performance testing demonstrated that the actuator achieves an axial displacement range of $±$2 mm, maintains a step resolution of 1 m under various loads, and delivers closed-loop positioning accuracy better than 1 m. This developed displacement actuator provides crucial technical support for the construction of ring solar telescopes and offers valuable references for engineering applications in other precision optical mirror support systems.

Keywords: Solar telescope; Support positioning; Stepper motor; Displacement actuator

1. Design of the Displacement Actuator

1.1 Design Specifications

The design requirements for the 2-meter ring solar telescope' s mirror differ from conventional full-aperture mirrors, demanding greater flexibility and precision from the positioning support and attitude adjustment systems. Table 1 summarizes the preliminary design specifications for the displacement actuator.

The actuator must support and adjust the primary mirror, requiring a maximum load capacity exceeding 200 N. To satisfy the drive motor' s stroke requirements in open-loop operation, the actuator must provide a total displacement range of $±$2 mm. Additionally, to meet correction capability requirements, the output displacement resolution must be no greater than 1 m, with closed-loop positioning accuracy also required to be no greater than 1 m.

1.2 Structural Configurations

Displacement actuators capable of simultaneously meeting the technical requirements of large stroke, high precision, and high load capacity typically employ one of three main structural configurations:

(1) **Displacement Scaling Type:** This configuration adds a displacement scaling mechanism after the drive element, primarily consisting of reducers, hydraulic reduction mechanisms, precision lead screws, and flexible hinges.

The performance of the scaling mechanism can be evaluated based on transmission ratio, backlash, response speed, and load capacity.

(2) **Inchworm Type:** Inchworm actuators operate on a "clamp-drive-clamp" principle, driven by piezoelectric ceramics, magnetostrictive materials, or shape memory alloys. While these driving elements offer high precision and fast response, enabling theoretically unlimited stroke, inchworm actuators suffer from complex control requirements and limited commercial availability.

(3) **Macro/Micro Hybrid Type:** This approach combines a macro stage for large-stroke, micron-level positioning with a micro stage for fine, nanometer-level positioning within a small range. The primary drawback is the complexity of both mechanical structure and control system [9].

Compared with the latter two configurations, the displacement scaling type offers a simpler mechanical structure and more convenient control. Through appropriate combination of drive elements and scaling mechanisms, it can deliver high-precision displacement output across a large stroke range. Based on the design specifications in Table 1, this design adopts the displacement scaling architecture.

1.3 Design Implementation

As shown in Figure 1 Figure 1: see original paper, a stepper motor integrated with a planetary reducer serves as the core driving element to achieve high-precision control and micro-displacement calibration. Both the stepper motor and actuator housing are flange-mounted and secured to the mirror cell. The motor shaft connects to a rotating nut via set screws, with the nut supported by bearings within the actuator housing. A linear screw with a 1 mm pitch mates with this nut, and a guide mechanism at the upper section of the screw converts the motor' s rotary motion into linear motion. To address inevitable backlash and lost motion in the internal guide rod and stepper motor mechanism, a preload spring elastic element applies axial preload to the linear motion rod. This preload element can absorb significant energy, mitigate vibration, and eliminate clearance. The upper end of the linear screw forms the displacement output interface, where a tension-compression sensor provides real-time load monitoring. A displacement sensor (LVDT) is integrated for output displacement measurement, with its mounting fixture attached to the actuator housing. A crossbeam connects the displacement output interface at one end and contacts the LVDT' s spherical tip at the other end. Figure 1(b) shows the 3D structural model, and Figure 1(c) presents the physical prototype.

Component List: 1. Stepper motor and reducer, 2. Flange, 3. Bearing, 4. Rotating nut, 5. Linear screw, 6. Preload spring, 7. Preload spring cap, 8. Housing, 9. Guide mechanism, 10. Tension-compression sensor, 11. Displacement output interface, 12. Crossbeam, 13. LVDT, 14. LVDT mounting fixture.

2. Performance Testing

Comprehensive performance tests were conducted on the displacement actuator, with the device installed on a dedicated test platform for all experiments.

2.1 Stroke and Linearity Testing

Due to nonlinear factors such as clearance, backlash, and friction in the drive motor and guide mechanism, output linearity testing was performed. The actuator was mounted on the test platform shown in Figure 2 [Figure 2: see original paper], and linearity was evaluated by operating the drive motor in open-loop mode through the full design stroke range (-2 to +2 mm) from the neutral position. A laser displacement sensor (Keyence H050, measurement range 0–10 mm, linearity $±$0.02% FS, repeatability 25 nm) recorded the actual full-scale output trajectory for linearity analysis, as shown in Figure 3 [Figure 3: see original paper].

Test results demonstrate bidirectional full-stroke capability with good linearity. The maximum residual error under linear fitting was 0.015 mm, indicating satisfactory linear performance across the entire stroke range in both directions.

2.2 Open-Loop Testing

Since LVDT accuracy directly affects primary mirror position measurement precision, LVDT calibration is critical. The selected LVDT has a linear error of 0.5% F.S.

The actuator was commanded to move from 0 mm to 5 mm stroke position, with the LVDT recording position changes. The displacement error curve in Figure 4 [Figure 4: see original paper] reveals non-uniform pitch along the screw thread length. Fourier fitting was applied to correct and compensate for this displacement error using the following function:

$$f(x) = a\sin(0.01x+b)+c\cos(0.01x+d)+a\sin(0.012x+b)+c\cos(0.012x+d)+a\sin(0.015x+b)+c\cos(0.015x+d)+$$

The fitted coefficients are listed in Table 2 .

Table 2 Fitted Coefficients

Coefficient	Value (mm)
a	-4.5884$×10^{-2}$
b	3.3674$×10^{-3}$
c	3.552$×10^{-4}$
d	-1.2271$×10^{-3}$
e	(value not specified)

The residual curve (Figure 4) shows maximum and minimum residual values of 0.0159 mm and -0.0162 mm, respectively, with an RMS residual of 0.0067 mm. These errors stem from suboptimal open-loop control accuracy, necessitating closed-loop control for correction.

2.3 Output Resolution Testing

Resolution testing evaluates the actuator’ s correction capability—its minimum controllable step size. Tests were performed under both compressive and tensile axial loads.

Compressive Load Test: The experimental setup is shown in Figure 5 [Figure 5: see original paper]. With a 2 kg compressive load, the output resolution test curve (Figure 6 [Figure 6: see original paper]) demonstrates that the actuator achieves 0.6 m step resolution, meeting the 1 m technical requirement.

Tensile Load Test: The tensile test setup appears in Figure 7 [Figure 7: see original paper]. Under a 1 kg tensile load, the output resolution test curve (Figure 8 [Figure 8: see original paper]) shows that the actuator achieves 0.4 m displacement resolution, satisfying the 1 m design specification.

The theoretical resolution without microstepping is 100 nm/step; the tests employed 2× microstepping. Figures 6 and 8 indicate that further microstepping is feasible. Inconsistencies in displacement across 15 individual steps result from motor clearance and friction effects.

2.4 Backlash Testing

Under a 2 kg compressive load at the 0.1 mm position, a single step pulse was applied, followed by an equal reverse motion with identical step count and size. The resulting position error, shown in Figure 9 [Figure 9: see original paper], reveals a 4.1 m error at the 0.1 mm position above center. This error arises from non-uniform screw pitch and structural elastic deformation under load, confirming that open-loop control precision is inadequate and requires closed-loop correction.

2.5 Closed-Loop Accuracy Testing

Based on the resolution test results showing open-loop resolution better than 0.6 m under various axial loads, closed-loop testing was performed. The control system drives the motor in open-loop mode while the LVDT sensor provides real-time displacement feedback for comparison with the target position, enabling closed-loop output.

Testing confirmed that the actuator achieves closed-loop output accuracy better than 1 m, meeting all technical specifications.

Conclusion

This paper presents the design and comprehensive testing of a stepper motor-driven displacement actuator. Test results demonstrate excellent output displacement linearity, satisfying the $±$2 mm axial stroke requirement with approximately 5 m thread clearance. Open-loop resolution exceeds 0.6 m, meeting the design target of less than 1 m. Closed-loop positioning accuracy achieves the technical goal of better than 1 m. However, non-uniform thread pitch leads to suboptimal open-loop precision, requiring closed-loop control for high-accuracy adjustment and positioning. The test results validate the actuator' s simple principle and structure, good maintainability, and compliance with design specifications, providing a valuable technical reference for axial support and adjustment of the 2-meter ring solar telescope' s primary mirror.

References

[1] Zhong Liu, Zhenyu Jin, Shu Yuan. The progresses of Chinese Giant Solar Telescope[C]// Proceedings of SPIE. 2014, 9145: 412-417.

[2] Zhong Liu, Zhenyu Jin. Simulation of Chinese Giant Solar Telescope[C]// Proceedings of SPIE. 2011, 8336: 54-62.

[3] Yang Changchun, Li Zhenggang, Chen Yuchao, Xu Jun. Design of the spectral scanning observation system for the 1-meter new vacuum solar telescope[J]. Astronomical Research and Technology, 2016, 13(02): 257-265.

[4] Liu Qing, Jiang Aimin. Research on optical path detection methods for optical synthetic aperture telescopes[J]. Astronomical Research and Technology, 2017, 14(04): 519-525.

[5] Zhong Liu, Zhenyu Jin, Yan Li, et al. Introduction to the 30m Ring Interferometric Telescope[J]. Proc. SPIE, 2006, 6267: 62672L.

[6] Wang Zhenglan, Yang Dehua, Wu Changcheng, Jin Zhenyu. Design and measurement of a bellows-based pneumatic force actuator[J]. Astronomical Research and Technology, 2018, 15(03): 347-353.

[7] Z. Liu, J. Xu, BZ. Gu. New vacuum solar telescope and observations with high resolution[J]. Research in Astronomy and Astrophysics, 2014, 14(6): 705-718.

[8] Yang Dehua. Calculation of geometric parameters and support mechanism for the primary mirror of the 2-meter ring solar telescope at Yunnan Observatories, Chinese Academy of Sciences - Summary report[R], College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, 2015.12.7.

[9] Bai Qingshun, Wang Qun, Zhang Qingchun, Liang Yingchun, Lou Zheng. Design and experiment of a cryogenic micro-displacement actuator[J]. Astronomical Research and Technology, 2016, 13(02): 199-204.

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