Postprint of Research on CAN Bus-Based Active Optics Mirror Pose Actuation System

Authors: Xiao Xinyi, Zongmeng Zhang, Yang Dehua, Wu Changcheng, Jin Zhenyu

Date: 2020-10-26T00:00:00+00:00

Abstract

For the pre-research of the primary mirror support system of the Advanced Ground-based Solar Telescope (AST-G), this paper designs an active optical mirror pose adjustment drive system based on CAN bus communication. First, for an active support prototype experimental platform, kinematic theoretical analysis and pose solution of the mirror were carried out, and then a master node and three slave nodes were designed using STM32 to realize distributed control of displacement actuators in the mirror pose drive system. Finally, performance testing of displacement actuators and experimental verification of mirror pose adjustment based on CAN bus were carried out. The results show that the control accuracy of the displacement actuator is better than 1 m RMS, the rotation error of the mirror around the X and Y axes is better than 1'' RMS, and the translation error of the mirror in the Z-axis direction is better than 1 m RMS. The research on the pose drive system based on CAN bus proposed in this paper provides technical exploration for the development of the primary mirror support system of the Advanced Ground-based Solar Telescope (AST-G), and can also provide reference for other active optical application systems.

Full Text

Development and Evaluation of a CAN-Based Alignment System for Active Optics

Xiao Xinyi[1]**, Zhang Zongmeng**[1]**, Yang Dehua**[1]**, Wu Changcheng**[1]**, Jin Zhenyu**[2]
[1] College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China
Email: dhyang@nuaa.edu.cn
[2] Yunnan Astronomical Observatories, Chinese Academy of Sciences, Kunming

650011, China
Email: kim@ynao.ac.cn

Abstract

In order to explore the primary mirror support system for the Advanced Ground-based Solar Telescope (AST-G), this paper presents the development of a CAN bus-based alignment drive system for active optical mirrors. Beginning with an active support prototype platform, we conducted kinematic analysis of the mirror and derived the pose solution algorithm. Subsequently, we designed a master node and three slave nodes using STM32 microcontrollers to achieve distributed control of displacement actuators within the mirror alignment system. Finally, we performed performance testing of the displacement actuators via CAN bus and experimentally verified the mirror alignment capability. The results demonstrate that the displacement actuator achieves control accuracy better than 1 m RMS, with rotational errors around the X and Y axes better than 1 arcsecond RMS, and piston error along the Z-axis also better than 1 m RMS. This research on the CAN bus-based alignment system provides valuable technical groundwork for the development of the AST-G primary mirror support system and offers a reference for other active optical applications.

Keywords: Active optics; CAN bus; Mirror alignment; Displacement actuator

Introduction

With the rapid advancement of modern astronomy, active optics technology has made it possible to manufacture large-aperture telescopes while maintaining excellent image quality [1-2]. The 500-meter Aperture Spherical radio Telescope (FAST) built by Chinese observatories employs active reflector technology, utilizing CAN bus for data transmission between controllers to drive displacement actuators [3]. The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), a major national scientific project, uses segmented mirror active optics with Ethernet-based communication and centralized-distributed control of displacement actuators for mirror positioning [4].

The Advanced Solar Telescope-Ground (AST-G) plans to implement active optics technology for its 8-meter primary mirror. To meet the pre-research requirements for AST-G's primary mirror alignment, this study draws on the successful experience of active mirror control from telescopes such as FAST and LAMOST to develop a CAN bus-based mirror alignment drive system. For the active support prototype system, we first performed kinematic analysis to derive the relationship between displacement actuator outputs and mirror pose, and established control specifications for actuators based on stepper motors integrated with planetary gearboxes. We constructed a distributed architecture mirror alignment system that controls each stepper motor individually while managing all sub-controllers through a main controller. Specifically, each sub-controller only needs to manage the pulse count, frequency, direction, and start/stop status of one stepper motor [5-7]. Using STM32, we designed one master node and three slave nodes to control the displacement actuators. CAN bus communication was selected for data transmission between sub-controllers and the main controller. This distributed one-to-one control architecture based on CAN bus effectively reduces the burden on the main controller, provides good independence for sub-modules, and enhances the flexibility of the pose control system.

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1. Overall Design and System Setup of Mirror Alignment System

As shown in Figure 1: see original paper, our experiments utilized a 700 mm aperture prototype active support system for flat glass mirrors, featuring nine-point axial pneumatic support and a six-bar 3-DOF (piston, tip/tilt) active adjustment mechanism [8], equipped with LVDT displacement sensors. Based on this prototype platform, we conducted experimental testing of the CAN bus-based mirror alignment system, including stability and repeatability tests, along with error analysis and correction. Mirror alignment is achieved by controlling three displacement actuators uniformly distributed on the primary mirror surface at a radius of 206 mm. The three actuators and their two-force-bar mechanisms enable active adjustment of three degrees of freedom. To monitor actuator displacement in real time, a Linear Variable Differential Transformer (LVDT) displacement sensor is integrated into each actuator [9]. The detailed adjustment mechanism is shown in Figure 1: see original paper, where the components are: 1. Mirror, 2. Invar pad, 3. Two-force-bar mechanism, 4. Tension/compression sensor, 5. Mirror cell plate, 6. Connecting flange, 7. Displacement actuator, 8. LVDT.

1.1 Mirror Kinematics Principle

From a kinematic perspective, we establish a coordinate system for mirror pose calculation as shown in [Figure 2: see original paper], with the mirror' s centroid as the origin, the mirror surface as the OXY plane, and the optical axis direction as the Z-axis.

Mirror alignment is accomplished by controlling three displacement actuators. In the figure, the adjusted positions of the actuators are denoted, and R represents the radius of the circle where the three displacement sensors are located. The rotation of the primary mirror around the X-axis (Rx) and Y-axis (Ry), as well as the piston motion along the Z-axis (Z), can be calculated from the displacement outputs of the three actuators.

From formulas (1), (2), and (3), the relationship between Rx, Ry, Z and d1, d2, d3 can be derived as shown in formula (4):

dR1d2d3ddRxRyRZ21321322arctan33xddddddddRRR 1313arctan33ydddddRRR 1233dddZ ZxRyR1d2

路由器 24V 供电电源主节点子节点 1 子节点 2 子节点 3 实验平台位移促动器 3 位移促动器 2 位移促动器 1

The inverse solution of formula (4) yields the relationship between d1, d2, d3 and Rx, Ry, Z.

From the theoretical formula (1) of the kinematic analysis, when d1 and d3 remain at the same horizontal position, the output resolution of d2 depends only on Ry, allowing calculation of the minimum resolution of displacement actuator d2 as shown in formula (5). Similarly, when Z remains constant, the output resolution of d1 and d3 depends on Rx and Ry, yielding the minimum resolution for actuators d1 and d3 as shown in formula (6).

1.2 System Architecture

1.2.1 CAN Bus-Based Alignment System Architecture Considering factors such as signal wire count, communication type, multi-master support, communication distance, speed, and maximum node capacity, we selected CAN bus for communication between master and slave nodes. CAN is a serial data communication protocol for data exchange between control and test instruments, supporting real-time and distributed control. The communication process is illustrated in [Figure 3: see original paper], comprising MCU, CAN controller, and CAN transceiver [10]. The MCU first sends messages to the CAN controller, which parses them into logic signals before transmitting to the CAN transceiver, which finally sends electrical signals onto the CAN bus via CAN_H and CAN_L lines. CAN communication not only reduces wiring complexity but also improves system reliability while reducing costs.

The overall system architecture is shown in [Figure 4: see original paper]. The mirror alignment system consists of three parts: host computer system, MCU module, and slave system. The host computer receives sensor data from the MCU via Ethernet, compares it with setpoints, configures actuator modes, sends control commands to the MCU, and performs data logging and real-time display. The MCU module receives sensor signals from slave nodes via CAN bus, passes them to the host computer, and transmits control commands from the host to the appropriate slave nodes. The slave system converts analog signals from nodes to digital via AD modules, sends them to the master node through the bus, and executes actuator control commands. This system offers high transmission rates, strong compatibility, robust fault tolerance, and excellent scalability.

The hardware design mainly includes the master node’ s MCU module, CAN communication module, Ethernet module, and the slave node’s AD sampling and motor driver modules. The host computer software involves test interface design and Ethernet communication programming to verify data transmission with slave systems. The slave software comprises master and slave node programs: the master node handles host communication and data exchange with slave nodes via CAN bus, while slave nodes implement CAN communication, stepper motor drive control, and sensor data acquisition.

1.2.2 Acceleration/Deceleration Characteristics of Displacement Actuator-Stepper Motor The displacement actuator’ s driving element is a stepper motor. Proper acceleration/deceleration profiles were designed to ensure smooth actuator operation, controlling angular displacement through pulse count. Pulses are generated by the microcontroller’ s timer PWM signals and fed to motor drivers. Given the distributed architecture, coordinated control of three actuator groups must be considered. With the three actuators moving 200 m RMS, 300 m RMS, and 500 m RMS respectively at different frequencies, the resulting motion curves are shown in [Figure 5: see original paper].

As shown in [Figure 5: see original paper], due to simultaneous motion and the prototype’ s mechanical structure, actuator d1 exhibits greater displacement, while actuators d2 and d3 experience step loss during open-loop operation. After closed-loop control, all three actuators reach their target positions at 35 seconds, demonstrating that the coordinated control method meets practical requirements.

2. Experimental Testing

2.1 Mirror Alignment System

As shown in Figure 1: see original paper, laser displacement sensors and inclinometers were used to measure the mirror’ s pose during experiments, with attitude sensors detecting rotational positions and laser sensors measuring piston along the Z-axis [11]. Using the alignment test system shown in [Figure 6: see original paper], the displacement actuator’ s minimum resolution is 0.1 m RMS without motor microstepping. For basic output resolutions of 1 arcsecond RMS for mirror tilt adjustments Rx and Ry, formulas (5) and (6) indicate that actuators d1 and d3 require resolution of 1.8 m RMS, while actuator d2 needs 1.7 m RMS.

2.2 Displacement Actuator Performance Testing

The actuator’ s correction capability was measured by testing its minimum controllable step size. Under a 5 kg load and without microstepping, the controller was commanded to execute identical step increments (5 steps each), producing the minimum correction capability curve shown in [Figure 7: see original paper]. The results show the actuator achieves a minimum step (displacement resolution) better than 1 m RMS even without microstepping.

Closed-loop control is implemented by comparing real-time LVDT feedback with target positions for compensation. With the actuator running 10 m RMS in closed-loop, both LVDT and laser displacement sensors recorded the motion curve shown in [Figure 8: see original paper]. The deviation between actual and target positions remains within 1 m RMS, confirming closed-loop output accuracy better than 1 m RMS.

2.3 Mirror Alignment System Performance Testing

With all three actuators of the prototype adjusted to level positions and placed in a laboratory environment, inclinometers recorded Rx and Ry variations while laser sensors monitored Z-axis displacement. The stability curves for Rx and Ry are shown in Figure 9: see original paper, and Z-axis stability in Figure 9: see original paper. Static errors remain within $±$0.2 arcseconds RMS for Rx and Ry, and $±$0.4 m RMS for Z-axis, demonstrating good system stability.

Repeatability was tested through closed-loop control by commanding the three actuators to move 120 m RMS, 200 m RMS, and -150 m RMS respectively for five cycles. Laser sensors measured Z-axis displacement while inclinometers monitored Rx and Ry. Repeatability curves are shown in [Figure 10: see original paper]: (a) for Rx, (b) for Ry, and (c) for Z-axis. The system exhibits repeatability errors of 2 arcseconds RMS for Rx and Ry, and 3 m RMS for Z-axis, attributed to mechanical structure and laboratory environment factors. Closed-loop correction using LVDT feedback was applied, with corrected rotation curves around X and Y axes shown in Figure 11: see original paper and (b), and Z-axis in Figure 11: see original paper. After correction, steady-state errors for Rx and Ry are better than 1 arcsecond RMS, and Z-axis error reaches within 1 m RMS.

Conclusion

This paper presents a CAN bus-based alignment drive system for active optical mirror positioning. Using CAN bus for data transmission between master and slave nodes, we established a distributed architecture to control stepper motors within displacement actuators, completing system hardware and software design and experimental validation. The results demonstrate that with LVDT-based displacement closed-loop control, actuator precision reaches 1 m RMS, steady-state errors for Rx and Ry are better than 1 arcsecond RMS, and Z-axis error achieves 1 m RMS. This preliminary exploration of CAN bus-based 3-DOF mirror alignment control provides valuable technical reserves for China' s under-development AST-G primary mirror support system and can be applied to distributed control of force actuators for other active optical mirror deformation applications.

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