A Preliminary Study on the Application of AC Servo Systems in Astronomical Telescopes (Postprint)

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Date: 2017-09-26T00:00:00+00:00

Abstract

AC servo systems have been widely applied in the industrial control field, but their application in the astronomical domain remains in its infancy. This study investigates the feasibility of applying AC servo systems to telescope mount control, using the Ground-based Wide-Angle Camera (GWAC)—a ground-based observation facility for the Sino-French astronomical satellite Space multi-band Variable Object Monitor (SVOM)—as the research platform. Key technical indicators including tracking speed control accuracy, right ascension tracking accuracy, maximum angular velocity, maximum angular acceleration, and repeat pointing accuracy were tested. The test results demonstrate that, compared with stepper motor systems, AC servo systems exhibit equally high precision in low-speed control. In the high-speed control domain, they possess a wider speed regulation range, faster speed adjustment, and smoother operation, representing distinct advantages. Additionally, they offer benefits such as low noise, high torque, and high cost-performance ratio. The experiment also measured the interference of AC servo systems on the Apogee CCD U9000, and the results indicate that the interference from AC servo systems on CCDs is minimal and within an acceptable range. In summary, AC servo systems are fully applicable for mount control of small-to-medium-sized astronomical telescopes, particularly for systems requiring fast slewing and pointing.

Full Text

A Preliminary Study on the Application of AC Servo Systems in Astronomical Telescopes

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Ground-based Wide-Angle Camera Space multi-band Variable Object Monitor

Abstract: AC servo systems have been widely applied in industrial control, but their application in astronomy remains in its infancy. Using the Ground-based Wide-Angle Camera Array (GWAC)—the ground observation equipment for the Sino-French astronomical satellite (SVOM)—as a research platform, this study investigates the feasibility of applying AC servo systems to telescope mount control. Key technical indicators including tracking speed control accuracy, right ascension tracking accuracy, maximum angular velocity, maximum angular acceleration, and repetitive pointing accuracy were tested. The results demonstrate that compared with stepper motor systems, AC servo systems achieve equally high precision in low-speed control. In high-speed control applications, they offer distinct advantages with wider speed regulation ranges, faster speed adjustment, and smoother operation. Additionally, AC servo systems feature low noise, high torque, and excellent cost-performance ratios. Experiments also measured the interference of AC servo systems on CCD imaging, revealing that such interference is minimal and within acceptable limits. In summary, AC servo systems are fully suitable for mount control of small-to-medium-sized astronomical telescopes, particularly for systems requiring rapid rotation and pointing.

Keywords: Ground-based Wide-Angle Camera Array; AC servo system; key technical indicators; CCD interference

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The Ground-based Wide-Angle Camera Array (GWAC) [1] is a telescope array composed of multiple wide-field telescopes. Each mount has a field of view of 12° × 12°, with a combined field of 24° × 24° across 9 units, making it the telescope array with the largest combined field of view. Located at the Xinglong Observatory in Hebei, the complete system will comprise 18 wide-field telescopes per mount, each with an aperture of 22 cm. The large field of view represents the most distinctive feature of GWAC, which will become the world' s largest telescope of its kind upon completion. Its primary scientific objectives include monitoring gamma-ray bursts [2] and detecting prompt gamma-ray radiation.

Fig. 1. GWAC prototype

GWAC Control Requirements

The GWAC equatorial telescope mount specifications define the technical indicators shown in Table 1 .

Table 1. GWAC Technical Indicators - Tracking speed control accuracy: 0.45 /s (RMS) - Pointing accuracy: 2 (RMS) - Continuous tracking for 5 minutes: better than 2 (RMS) - Maximum angular velocity: 1.5°/s - Maximum

angular acceleration: 0.5°/s^2

The control system employs a two-level architecture with upper and lower computers. The lower computer resides in an electrical control box adjacent to the mount, while the upper computer operates in the control room. Communication between levels uses network protocols. Both incremental rotary encoders and linear scales must be installed—the latter for telescope position measurement and the former primarily for position protection.

Based on GWAC' s scientific objectives, the following functional requirements were established: - The system must support fast and slow motion adjustments for both right ascension and declination axes, essential for telescope pointing and daily maintenance. - Right ascension must support sidereal tracking speeds adjustable between 14 /s and 16 /s in 0.1 /s increments, with a default setting of 15 /s. - The control software must include hardware testing capabilities to verify stability and accuracy during pointing and tracking operations, enhancing system maintainability. - Software protection functions are required, enabling the telescope to automatically stop or reject pointing commands when the current or target position exceeds safe operating limits, thereby improving operational safety.

According to fundamental requirements for astronomical telescope control systems, the mount must achieve both stable, precise tracking speeds and accurate positioning/guiding. Using a three-closed-loop servo control principle [4] with current loop, velocity loop, and position loop, we designed the GWAC mount control system. The current loop forms the innermost loop, the velocity loop serves as the intermediate loop, and position control constitutes the outer loop.

Fig. 2. The principle of GWAC telescope servo control system

This typical three-closed-loop system comprises the current loop inside the servo driver, the velocity loop using an incremental encoder as the speed sensing element, and the outer position loop using a linear scale as the angle measurement device.

The current loop regulates current to ensure proper torque output and smooth operation, directly affecting the declination axis motor' s startup and acceleration/deceleration performance. During telescope pointing, the outer position loop dominates by comparing real-time position feedback with target axis angles to achieve right ascension and declination positioning. Positioning accuracy is influenced by external disturbances such as atmospheric refraction and by the linear scale' s measurement precision. Although the velocity loop doesn' t affect final positioning results, real-time velocity feedback improves speed curve smoothness and telescope operational stability [5].

After pointing completion, the system enters tracking mode. The theoretical tracking speed is 15 /s, moving from east to west. Tracking speed characteristics critically determine observation quality, making precision and stability paramount. The servo controller generates control signals based on programmed setpoints, driving the motor while encoder feedback ensures velocity accuracy. Encoder stability and line count per revolution decisively impact speed stability and precision.

Based on this control principle, the GWAC servo system primarily employs feedback based on servo algorithms combined with feedforward control principles [6].

Hardware System Design and Component Selection

Based on the servo control principle, the hardware system comprises three main components: system management and control level, measurement and feedback units, and execution units.

System Management and Control Level The upper control computer serves as the system management level, issuing telescope control commands. Communication between the control computer and servo controller occurs via network protocols for data and command exchange, with real-time telescope position display. We selected the Leadshine SMC6490 motion controller, a general-purpose independent 10/100M Ethernet-based multi-axis motion controller supporting multi-controller and multi-computer configurations. Functioning as a dedicated computer, it enables human-machine interaction and provides stable signal transmission through short-distance transmission of control pulse signals to drivers and feedback signals from linear scales, reducing electromagnetic interference.

Servo Control Unit The servo control unit utilizes a Panasonic three-phase AC servo driver (MEDKT7364CA1) with a dedicated connector for controller communication. The driver interface connects directly to the control computer, allowing parameter configuration through specialized software for convenient tuning. Control signals employ pulse train formats.

Servo Execution Unit The execution unit employs a Panasonic three-phase AC servo motor (MDME202GCGM) with a rated output power of 2.0 kW, rated torque of 9.55 N · m, and maximum speed of 2000 r/min.

Measurement and Feedback Unit The axis angle measurement and feedback unit uses a Renishaw linear scale with a 206 mm measurement length, 20 m grating pitch, and 0.1 m readhead resolution, providing high control precision. The velocity measurement and feedback unit employs a 2000-line incremental encoder.

Software System Design

The software development environment uses Windows 7 with Visual Studio 2010 as the platform and C++ as the language, employing object-oriented development techniques.

Design Philosophy and Program Structure Telescope mount control involves two primary functions: pointing and tracking. Pointing demands rapid, accurate positioning, while tracking requires high precision. Effective coordination and transition between these modes is essential. The system must display commanded versus actual positions in real-time during telescope operation. We implemented a timer to continuously acquire the telescope' s hour angle and calculate right ascension. Leveraging Windows APIs, the system obtains Universal Time and Beijing Time, computing sidereal time through astronomical algorithms for observer reference.

Precise timing systems are crucial for pointing accuracy. The software interface primarily relies on the MFC class library [7] for implementation. To facilitate telescope debugging, both fast and slow adjustment modes are provided to meet varying position adjustment needs for test personnel.

A multi-threaded approach creates a data acquisition module that captures telescope movements and displays them in real-time on the interface. Considering transmission speed and reliability, the controller employs network communication. Based on design philosophy and functional requirements, the program framework is shown in Fig. 3.

Fig. 3. The frame of program

Control Interface Implementation The control interface development primarily utilizes MFC with VS2010 as the platform. Key classes include Button, Edit Control, IP Address Control, and Static Text, which provide standard implementation methods for user interfaces. This technology enables convenient framework interface calls, combining various class libraries into an application framework for efficient programming and human-machine interaction. The GWAC control interface is shown in Fig. 4.

Fig. 4. The control interface of GWAC telescope

The interface' s upper-left section contains connection status, world time, and sidereal time displays. The telescope status feedback bar provides real-time action updates. Controller connection/disconnection results appear in the interface title bar. The telescope pointing and tracking panel shows commanded right ascension/declination versus actual values in real-time. The right ascension control panel features fast/slow adjustment buttons for east/west directions with adjustable tracking speed (default: 15 /s). The declination control panel includes north/south adjustment buttons.

Experimental Testing of GWAC AC Servo System

Using identical controllers and software on the GWAC prototype, we tested both AC servo motors and stepper motors (Japanese RORZE RM28G06S) to compare their performance across key technical indicators: tracking speed control accuracy, maximum angular velocity, maximum angular acceleration, right ascension tracking accuracy, and repetitive pointing accuracy. We also conducted experimental studies on AC servo system interference with CCD imaging.

Key Technical Indicator Measurements

Tracking Speed Control Accuracy The test method controlled the right ascension axis at 15 /s. The control software recorded angular displacement at 200 ms intervals to calculate angular velocity. The tracking speed curve under AC servo motor drive is shown in Fig. 5, with a speed peak-to-peak value of 1.6 /s and control accuracy of 0.30 /s (RMS). The curve under stepper motor drive is shown in Fig. 6, with a speed peak-to-peak value of 1.6 /s and control accuracy of 0.28 /s (RMS).

Fig. 5. Tracing speed curve of AC motor

Fig. 6. Tracing speed curve of stepper motor

Maximum Angular Velocity The test method commanded the right ascension axis to rotate at maximum target speed. The AC servo motor achieved 5.01°/s, while the stepper motor reached 1.87°/s.

Maximum Angular Acceleration The test method accelerated the right ascension axis to maximum speed, then decelerated to stop, repeating the process in the opposite direction while recording linear scale displacement at 0.2 s intervals. The AC servo motor achieved $3.57°/s^2$, while the stepper motor reached $1.11°/s^2$.

Right Ascension Tracking Accuracy The test method tracked near the zenith for 5 minutes with 10 s CCD exposures. The tracking accuracy curves for AC servo and stepper motors are shown in Fig. 7 and Fig. 8, respectively. The AC servo motor achieved 1.0 (RMS), while the stepper motor achieved 1.4 (RMS). Both systems demonstrate comparable precision in low-speed control and meet requirements, but the AC motor' s maximum speed and acceleration significantly exceed the stepper motor' s, offering superior high-speed performance.

Fig. 7. The tracking accuracy of AC motor

Fig. 8. The tracking accuracy of stepper motor

Repetitive Pointing Accuracy The test method commanded the telescope to point to position A, track, and capture an image, then repeated this process multiple times. Image processing software calculated each image' s field center coordinates, and Excel computed the RMS deviation from the mean. Table 2 presents the field center coordinates and repetitive pointing accuracy for positions A and B, achieving 14.2 (RMS) and 18.5 (RMS) respectively, meeting design requirements.

Table 2. The statistics of field center coordinates and repetitive pointing accuracy

AC Servo System Interference with CCD Imaging

To determine whether AC servo systems affect CCD imaging and whether interference levels are acceptable, we conducted experimental studies.

Interference Principle Analysis

CCD noise characteristics critically impact imaging quality. CCD noise comprises photon noise [8], dark current noise, and readout noise. Photon noise occurs during shutter-open exposure. Dark current noise stems from semiconductor thermal excitation, making temperature a critical factor—dark current increases exponentially with temperature. To minimize dark current, CCDs incorporate cooling systems. Dark current also correlates with integration time, increasing with longer exposures.

Readout noise [9] originates from the analog-to-digital conversion quantization noise [10] across all pixel Analog-to-Digital Units (ADUs), including circuit reset noise and output amplifier noise. Readout noise is independent of exposure time but directly relates to readout speed.

Although AC servo systems implement grounding and driver housing shielding, electromagnetic interference persists due to: switching noise from power electronic device commutation, inrush currents and switch jitter during load startup, and interference from high-speed digital circuits within the unit [11]. Power transmission lines supplying the motor also generate interference. Consequently, AC servo system interference with CCDs primarily affects electronic circuits, mainly impacting readout noise.

Using the GWAC AC servo system as a test platform, we conducted interference tests on the Apogee CCD U9000x, using readout noise as the reference metric. To avoid photon and dark current noise effects, we selected bias exposure mode (shutter closed) at -15°C. Image subtraction algorithms eliminated ramp noise and pixel non-uniformity.

Experimental Method and Data Processing

Tests were conducted under four conditions: (1) AC servo system off, (2) AC motor no-load constant rotation, (3) AC motor driving right ascension axis with load at constant speed, and (4) AC motor driving the axis through multiple acceleration/deceleration cycles during exposure (maximum speed: 248 r/min). For each condition, we captured multiple bias images. Using MaxIm image processing software and MATLAB, we applied image subtraction (subtracting the first image from subsequent images in each set) and calculated the standard deviation of ADU values across all pixels as the readout noise metric.

Test Results Analysis

Given the massive data volume (each image requiring significant storage), we developed MATLAB 2012-based image processing and calculation software. The readout noise distribution curves for the four test conditions are shown in Fig.

9. The data exhibit no significant jumps, remaining within narrow ranges, indicating minimal interference during motor constant rotation and acceleration/deceleration.

The average readout noise without AC servo activation was 8.2861 ADU. Under no-load constant rotation, loaded constant rotation, and loaded acceleration/deceleration conditions, the averages were 8.2799, 8.2717, and 8.2774 ADU, respectively. Relative errors compared to the non-activated state were 0.07%, 0.17%, and 0.10%—all below 0.5%. Thus, AC servo system interference with the Apogee CCD U9000x does not affect observation data quality, confirming suitability for telescope control.

Fig. 9. The distribution curve of readout noise for the four cases

Conclusions

This study developed a servo control system for telescope mounts based on control requirements, selecting hardware for control loops and axis angle measurement/feedback, and implementing software control systems. Network communication with the controller enables command transmission through programming interface functions. The design incorporates major functional modules for communication and auxiliary observation information, achieving visual interface control.

Experimental measurements of tracking speed control accuracy, maximum angular velocity, maximum angular acceleration, right ascension tracking accuracy, and repetitive pointing accuracy demonstrate that AC servo system performance meets design requirements. Comparative testing on the same platform reveals that AC servo systems match stepper motor precision in low-speed control while offering superior performance in high-speed applications with wider speed ranges and higher response frequencies.

Experimental studies on AC servo system interference with CCD imaging show that interference primarily affects readout noise. Comparing readout noise across four conditions (servo off, no-load constant rotation, loaded constant rotation, and loaded acceleration/deceleration) reveals relative errors below 0.5% during servo operation. This confirms that AC servo system interference with the Apogee CCD U9000x does not compromise observation quality, validating its suitability for telescope control applications.

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