Control and Image Acquisition for the Dual-Field Terminal of the Lijiang 2.4m Telescope (Postprint)

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Abstract

To fully utilize the limited Cassegrain focus interface of the Lijiang 2.4-meter telescope and enhance observation efficiency, a dual-field astronomical observation terminal has been developed. This terminal enables the implementation of various parameters such as field of view and image scale on the 2.4-meter telescope for conducting astronomical observations including fast photometry and high-resolution imaging, thereby satisfying the diverse observational requirements of astronomers. To meet the terminal' s precision requirements for the filter wheel and switching between large-field-of-view and small-field-of-view optical paths, as well as the speed requirements for EMCCD camera image acquisition, this paper employs three-layer motor closed-loop control and multi-threaded concurrent execution technologies to achieve precise control of the filter wheel and optical path switching, along with rapid EMCCD image acquisition and storage. Comprehensive laboratory testing demonstrates that the designed control and image acquisition system satisfies all specified performance and functional metrics of the terminal.

Full Text

Control and Image Acquisition of the Dual-FOV Terminal on Lijiang 2.4-meter Telescope

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Abstract

To fully utilize the limited Cassegrain focus interface of the Lijiang 2.4-meter telescope and improve observation efficiency, we have developed a dual-field-of-view (dual-FOV) astronomical observation terminal. This terminal enables variable field-of-view and image scale parameters on the 2.4-meter telescope for astronomical observations such as rapid photometry and high-resolution imaging, thereby meeting the diverse observational requirements of astronomers. Addressing the terminal' s stringent demands for filter wheel positioning accuracy, precision switching between large-FOV and small-FOV optical paths, and high-speed image acquisition from the EMCCD camera, this paper employs three-layer closed-loop motor control and multi-threaded concurrent execution technologies to achieve precise control of the filter wheel and FOV switching, as well as rapid image acquisition and storage from the EMCCD camera. Comprehensive laboratory testing demonstrates that the designed control and image acquisition system meets all specified performance and functional requirements of the terminal.

Keywords: 2.4m telescope; dual-FOV terminal; positional accuracy; rapid image acquisition

Introduction

Currently, China operates only two 2-meter-class ground-based optical telescopes: the Xinglong 2.16-meter telescope and the Lijiang 2.4-meter telescope [1]. However, astronomical research encompasses numerous targets, and different scientific objectives require matching terminal instruments, while telescope interfaces are limited and cannot accommodate all desired equipment simultaneously [2]. The Lijiang 2.4-meter telescope has five available Cassegrain focus interfaces, currently occupied by five major terminal instruments: the PICCD camera, the Yunnan Faint Object Spectrograph and Camera, the Lijiang Exoplanet Tracker, the High Dispersion Spectrograph, and the China Yunnan Integral Field Spectrograph [3-4]. To satisfy astronomers' diverse observational needs, we have developed a dual-FOV astronomical observation terminal for the Cassegrain focus of the 2.4-meter telescope. This terminal aims to modify observation system parameters such as field-of-view and image scale to enable rapid photometry and high-resolution imaging for studying fast time-varying astronomical phenomena, including large-scale, short-timescale optical flickering and flare activity in stars, ultra-short-period eclipsing binary systems, and sub-arcsecond timescale stellar pulsations [5-6]. It also plays a crucial role in studying faint companions and solar system planets by using short exposures to eliminate atmospheric turbulence effects on image quality, preserving high-frequency information from target sources and reconstructing near diffraction-limited high-resolution images that can accurately restore fine structural details [7-8].

1. Requirements for the Control and Image Acquisition System

The dual-FOV terminal employs a dual-channel confocal optical system covering the 350nm-950nm wavelength range. Its fundamental principle and physical implementation are shown in [Figure 1: see original paper]. The frontmost component is a filter wheel housing five bandpass filters (U, B, V, R, I) and one compensation plate. Following the filter wheel is the Cassegrain focal plane of the 2.4-meter telescope, which serves as the object plane for this terminal. Subsequent optical elements include a front fixed lens group, a zoom lens group (comprising high-magnification and low-magnification lens groups for small-FOV and large-FOV imaging respectively), a rear fixed lens group, and the EMCCD detector. The high- and low-magnification lens groups in the zoom assembly are time-shared, meaning they do not appear simultaneously in the optical path. The front lens group, rear lens group, and EMCCD are common to both FOV configurations.

When operating in small-FOV mode, the terminal provides an F/32 focal ratio, 0.85 field-of-view, and 0.035 pixel scale on the EMCCD. In large-FOV mode, it delivers F/3 focal ratio, 9 field-of-view, and 0.37 pixel scale. During observations requiring different fields-of-view, the control system must rapidly and precisely execute automatic switching between high- and low-magnification lens groups and between filters, with switching times under 30 seconds. Based on optical system imaging quality requirements, lens group positioning accuracy must be better than ±2 , while filter switching accuracy must exceed ±5 . To enable statistical reconstruction of high-resolution images, the EMCCD must rapidly acquire and store large sequences of speckle images. Additionally, rapid photometry demands fast acquisition of numerous images. The image acquisition and storage system must operate continuously and stably while fully exploiting the EMCCD camera’ s maximum acquisition rate.

2.1 System Architecture

The overall system architecture is illustrated in [Figure 2: see original paper]. The system comprises three main components: (1) optical path switching control between high- and low-magnification lens groups, (2) filter wheel rotation control, and (3) EMCCD camera control with image acquisition and storage. All three modules are integrated into a single control computer. Both lens group switching and filter wheel rotation utilize separate motors driven by the same multi-axis driver, with a 1:1 direct drive ratio between motor and load to eliminate intermediate errors from transmission systems. Both motors employ Beckhoff AM8013 synchronous servo motors equipped with 18-bit absolute encoders providing better than 0.5 resolution and 5 accuracy. Motor shafts also feature holding brakes to lock the axis when the system reaches position. The motor drive controller uses the Beckhoff AX5203, which can simultaneously control both motors. Motors, encoders, and brakes connect to the driver via

OCT cables, and the driver communicates with the computer through EtherCAT fieldbus. Motor position planning, position and speed control algorithms, and logic control are implemented on the Beckhoff real-time kernel TwinCAT3.0 [10], then integrated with image acquisition software through API functions to enable information exchange for motor status, position feedback data, and human-machine control interfaces.

The EMCCD camera is an Andor iXon Ultra 888 model with a 1024×1024 pixel array, 13 m pixel size, and 16-bit A/D conversion, producing 2MB per frame at a full-frame readout speed of 26 fps. Camera control and image acquisition connect to the control computer via USB3.0.

Since the large-FOV and small-FOV systems are time-shared but both require rapid image acquisition and storage, and observations demand different filters, the overall observation control flow proceeds as follows: (1) Select the desired field-of-view based on observational requirements, switch to the corresponding lens group, and verify positioning via encoder feedback; (2) Select the appropriate filter based on observation band and verify filter wheel positioning via encoder feedback; (3) Point the telescope to the target and monitor real-time camera images to determine when to begin acquisition; (4) Execute image acquisition and storage while determining whether to conclude the session; (5) Upon completion, reset the system and decide whether to conduct subsequent observations or shut down.

2.2 Filter Wheel and Lens Group Switching Control

The control structure for both filter wheel and lens group switching employs an identical three-layer closed-loop architecture, comprising from inner to outer loops: current loop, velocity loop, and position loop, controlling motor current, velocity, and position respectively. This control structure is shown in [Figure 3: see original paper]. Current control algorithms execute in the AX5203 driver, while velocity and position control algorithms run on the TwinCAT3.0 kernel [11]. All control algorithms utilize PID control: current and velocity loops ensure smooth motor operation, while position control guarantees system positioning accuracy. Implementation of each control mode on the TwinCAT3.0 development platform is shown in [Figure 4: see original paper]. Figure 4(a) illustrates the three-layer closed-loop control implementation, where the position loop uses proportional-only control (P-control in PID), while velocity and current loops employ proportional-integral control (PI-control). Figures 4(b), 4(c), and 4(d) detail the current, velocity, and position loop structures respectively, including inputs, outputs, feedback, integration time, signal limiting, and acceleration/deceleration profile planning.

2.3 EMCCD Camera Control and Image Acquisition

EMCCD camera control functions include mechanical shutter, electronic shutter, cooling temperature, exposure time, exposure mode, multiplication gain, and acquisition speed performance control [12]. To achieve rapid photometry and sequential speckle image acquisition, the camera operates in continuous acquisition mode, with multiplication gain freely adjustable based on target magnitude and exposure time requirements. To enable continuous camera exposure with maximum-speed readout and continuous image acquisition and storage, the system employs multi-threading technology, with image acquisition and storage threads assigned the highest priority. The image acquisition flow is shown in [Figure 5: see original paper].

To enhance acquisition speed and system stability, a 100-frame image buffer is established between image acquisition, storage, and display threads. These threads employ mutual locking mechanisms to synchronize and share data, reducing inter-thread blocking and improving system speed and stability.

2.4 Software and Human-Machine Interface Design

The control and image acquisition software architecture runs image acquisition and motor control in separate processes, while camera control, image acquisition, storage, display, and switching mechanism interfaces operate in different threads within the image control process. The software is implemented on Windows 7 using MFC development in Visual Studio 2015. System switching, filter wheel control, camera control, image acquisition, and human-machine interfaces are visualized as shown in [Figure 6: see original paper]. This interface provides camera start/stop, shutter and acquisition mode settings, temperature control, storage configuration, image display, and camera status monitoring. It also includes target position selection, current position display, and brake control for both lens group switching and filter wheel motors. Motor control executes in the TwinCAT3.0 background kernel, and communication between the human-machine interface for high/low magnification lens group switching and filter wheel control and the motor control programs in the TwinCAT3.0 kernel utilizes API functions provided by TwinCAT3.0.

3.1 Motor Control Loop Parameter Tuning for Filter Wheel and Lens Groups

Based on [Figure 4: see original paper] and targeting stable motor operation, the system was debugged using step response curves as the evaluation criterion to tune PID parameters for each loop. The process proceeds sequentially: starting with the current loop, adjust PID parameters while monitoring step response and steady-state error of current output until stable; then tune velocity loop PID parameters while monitoring velocity output stability; finally tune position loop PID parameters while monitoring position step response and steady-state error.

System debugging with actual loads yielded the final PID parameters for each closed-loop control circuit as shown in .

3.2 Filter Wheel Switching Position Accuracy Testing

Since the filter wheel is directly driven by the motor, the absolute encoder on the motor shaft directly indicates the filter wheel’s actual angular position. However, the precise absolute position of each filter (corresponding to the encoder’ s actual position) must be calibrated optically. For laboratory testing of control positioning accuracy, the six filter wheel positions were temporarily assigned encoder values of 0°, 60°, 120°, 180°, 240°, and 300°. The filter wheel motor was then controlled to reciprocate to these points, testing forward (encoder reading increasing) and reverse (encoder reading decreasing) positioning repeatability at each point. The error between encoder feedback values and commanded values was recorded for 200 measurement cycles, collecting 200 error values for statistical analysis. Test results are shown in [Figure 7: see original paper]: Figure 7(a) shows forward positioning accuracy at the 120° position, Figure 7(b) shows reverse positioning accuracy at 120°, while Figures 7(c) and 7(d) show forward positioning accuracy at 60° and 180° respectively.

To verify that any single control cycle meets requirements, statistical error peak-to-valley (P-V) values, maximum positive deviation, and maximum negative deviation were analyzed. For the 120° position, forward and reverse P-V values are 0.36 and 0.42 respectively, with maximum positive deviations of 0.18 and 0.24 , and maximum negative deviations of -0.18 and -0.18 . These results demonstrate that filter wheel positioning accuracy in both directions meets the system requirement of ±5.0 . Comparing different positions, the P-V values at 120°, 60°, and 180° are 0.36 , 0.49 , and 0.60 respectively, with maximum positive deviations of 0.18 , 0.25 , and 0.30 , and maximum negative deviations of -0.18 , -0.24 , and -0.30 . This confirms that positioning accuracy at any point satisfies the ±5.0 system requirement.

3.3 Lens Group Switching Position Accuracy Testing

Identical to the filter wheel structure, the lens group switching motor directly drives the switching mechanism. Both positions also require optical calibration. For laboratory control system positioning accuracy testing, two points were set at 120° (small-FOV system) and 300° (large-FOV system). With 200 measurement cycles, error distributions are shown in [Figure 8: see original paper].

Figures 8(a) and 8(b) show P-V values of 0.54 and 0.66 respectively, with maximum positive deviations of 0.24 and 0.30 , and maximum negative deviations of -0.30 and -0.36 . These results indicate that positioning accuracy for both small-FOV and large-FOV systems meets the ±2.0 system requirement.

3.4 Image Acquisition System Testing

Image acquisition system testing includes functional camera control tests and speed/stability performance tests. While functional testing is straightforward, this paper focuses on performance testing, specifically acquisition speed and stable operation at the camera' s maximum rate. Test results are shown in [Figure 9: see original paper]. Figure 9(a) presents short-timescale testing: speed variation during 5,000 continuous frames, with acquisition speed calculated from inter-frame time differences, yielding an average speed of 25.79 fps and P-V fluctuation of 0.25 fps. Figure 9(b) shows long-timescale testing: 2-hour continuous acquisition with speed calculated from frames captured per minute, resulting in an average speed of 25.78 fps and P-V fluctuation of 0.30 fps. Both short- and long-timescale results demonstrate that the camera operating speed is comparable to the theoretical 26 fps value, confirming that the image acquisition system fully exploits the camera' s maximum acquisition rate while maintaining stable operation.

Conclusion

The Lijiang 2.4-meter dual-FOV astronomical observation terminal has completed optical-mechanical-electrical integration testing in the laboratory, with detailed performance and functional testing of the control and data acquisition systems. While the fixed offset between position encoders and optical alignment requires further optical calibration, this bias is constant and does not affect test results for filter wheel and FOV switching accuracy. Therefore, the testing methodology is valid, and results demonstrate that the terminal' s control and image acquisition systems achieve all design specifications.

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