Motion Control Implementation of the NVST Polarimetric Observation System (Postprint)

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Abstract

The 1-meter New Vacuum Solar Telescope (NVST) at Yunnan Observatories is the primary facility in China for optical and near-infrared observations of the Sun in the fields of solar physics and space science, with its main scientific objective being high-precision, high spatiotemporal resolution measurements of solar magnetic fields. NVST employs a mechanically scanning polarimetric observation mode. Due to the structural characteristics of its optical system, the telescope inevitably introduces time-varying polarization effects during solar tracking, necessitating systematic calibration during polarimetric observations. The entire system comprises a calibration unit, an analysis unit, and a detector, with multiple moving components that all have complex and precise motion requirements. Based on the motion requirements of each optical component during both the polarimetric calibration and observation processes, the control requirements for the calibration unit and analysis unit have been specified, and the motion requirements for each component under different observation modes have been implemented. A remote control scheme based on the TCP/IP protocol has been adopted, integrating various commercial drive controllers that utilize serial communication. A set of calibration unit control software and corresponding user interface has been developed under the .NET framework, with an OCS interface reserved. Performance tests demonstrate that the system meets the requirements for actual observations and has now been put into operation, laying the foundation for subsequent polarimetric observations.

Full Text

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Abstract

The 1-meter New Vacuum Solar Telescope (NVST) at Yunnan Observatories is a key facility for optical and near-infrared solar observations in China's solar physics and space science research, with high-precision, high spatiotemporal resolution measurement of solar magnetic fields as its primary scientific objective. NVST employs a mechanically scanned polarization observation mode. Due to the structural characteristics of its optical system, the telescope inevitably introduces time-varying polarization effects during solar tracking. Therefore, system calibration is required for polarization observations. The entire system comprises a calibration unit, an analysis unit, and a detector, with multiple moving parts that demand complex and precise motion control. This paper addresses the motion requirements of various optical components during polarization calibration and observation processes, presents the control specifications for the calibration and analysis units, and implements the motion requirements for each component under different observation modes. Based on a remote control scheme using the TCP/IP protocol, we integrated various commercial drive controllers that utilize serial communication, and developed a calibration unit control software with a corresponding user interface under the .NET framework, with an OCS interface reserved for future integration. Performance testing demonstrates that the system meets practical observation requirements and has been put into operation, laying the foundation for subsequent polarization observations.

Keywords: Polarization observation; Calibration unit; Control scheme; Remote control

Introduction

In the vast universe, the Sun is the celestial body most closely related to humanity and the nearest star that can be studied in depth [1]. Magnetic field lines of different origins interweave throughout all parts of the solar atmosphere, with magnetic field activity playing a dominant role in the structural evolution of the solar atmosphere [2]. To more deeply understand and investigate the physical mechanisms of solar activity, many observatories and research institutions worldwide have made magnetic field measurement a key research objective. Instruments such as the New Solar Telescope (NST) at the Big Bear Solar Observatory in the United States, the Domeless Solar Telescope (DST) in Japan [3], the Swedish 1-m Solar Telescope (SST) [4], and the 1.5-meter GREGOR Solar

Telescope in Germany [5-6] have all been used for fine-scale observations of solar magnetic fields and have achieved remarkable results. The Solar Magnetic Field Telescope at the Huairou Solar Observing Station of the National Astronomical Observatories [7] and the Stokes Spectral Telescope at Yunnan Observatories [8] have also made outstanding contributions to polarization measurements of solar magnetic fields.

Since its establishment, the 1-meter New Vacuum Solar Telescope has made high-resolution spectroscopic observations of magnetic fields in solar active regions a key scientific objective [9]. Polarization spectroscopic observations based on a spectrometer have been realized, and the development of a two-dimensional high-resolution magnetograph based on a narrowband filter is underway. Both polarization spectroscopic observations and the two-dimensional magnetograph are modulated by the telescope system, necessitating polarization calibration of the telescope system [10-11].

The 1-meter solar telescope employs an alt-azimuth mount structure with a modified Gregorian optical system that uses multiple folding mirrors after the F2 focal point, as shown in [Figure 1: see original paper]. During solar tracking, the relative orientation angles between these mirrors (the M3, M4, M5, M6, and M7 components in Figure 1) change with the telescope's altitude and azimuth angles, introducing time-varying polarization effects into the telescope system. To obtain the true polarization spectrum of solar active region targets at each moment, a polarization calibration unit must be installed in the symmetric optical path of the telescope for real-time calibration. Considering the actual working environment of the NVST polarization observation system, the calibration unit adopts a TCP/IP-based remote control approach.

1 Overall Design of the Polarization Observation System

Currently, in the field of astronomical observations, solar magnetic field measurements primarily rely on the Zeeman effect of solar spectral lines, typically using Stokes parameters to interpret the polarization state produced by solar magnetic fields [12]. The NVST polarization observation system can be functionally divided into two parts: a calibration unit and an analysis unit. During solar polarization observations, the calibration unit is moved out of the optical path while the analysis unit operates. During system calibration, the calibration unit is inserted into the optical path and works together with the analysis unit to obtain a correction matrix for observational errors. According to the overall design of the polarization observation system, the analysis unit is placed near the F3 focal point on the instrument platform, while the calibration unit is located at the F2 optical focus inside the vacuum main tube of the 1-meter solar telescope, as shown in Figure 1. In addition to their own operational motions, both the analysis and calibration units also move with the spectrograph tube and the telescope as a whole, making the control signal and power supply design for the two units rather complex. Furthermore, for the calibration unit, whether being inserted into or removed from the optical path, it must not block the optical path or destroy the symmetry of the optical path, requiring optimized mechanical design.

2 Motion Schemes for the Calibration and Analysis Units

The calibration unit is used to generate polarization light with known polarization states. Its main component must be controlled by a stepper motor to achieve two modes: inserted working status and removed from the optical path, as shown in [Figure 2: see original paper]. To meet different field-of-view requirements during observations, an adjustable field stop is installed at the F2 focal point and controlled by a separate stepper motor to switch between different observation field sizes.

The calibration unit employs a quarter-wave plate and a reflective polarizer to form a polarization generator. The wave plate and polarizer should be mounted on two independent ultrasonic motors with through-holes. According to optical requirements, the two motors drive the rotation to combine and produce six groups of polarization light with known states ($I \pm Q$, $I \pm U$, $I \pm V$) required for calibration. The polarization analyzer at the telescope's F3 focal point measures the polarization light after it passes through the telescope's folding mirror group.

The polarization analyzer consists of a rotatable wave plate with a retardation of 127.8°@5324Å and a fixed polarizer. The wave plate rotation is also directly driven by a hollow ultrasonic motor, as shown in [Figure 3: see original paper]. Theoretically, measurement intensities at different wave plate positions should be symmetrical, but actual measurements show some differences. Therefore, the polarization analyzer only uses 0 to 180 degrees for measurements. After completing a set of polarization measurements, to avoid measurement errors caused by asymmetry, the motor should rotate back to the optical zero point before starting the next measurement. The only drawback of this approach is an additional equipment operation time loss of approximately 500 ms.

During calibration observations, the calibration unit needs to combine 81 states in total. These states are redundant to improve accuracy. For each polarization state combination of the calibration unit, the wave plate in the polarization analyzer rotates to 8 positions, and the light intensity at each position is measured. Based on the known polarization states generated by the calibration unit and the measurement results from the polarization analyzer, the polarization characteristics of the telescope system (i.e., the Mueller matrix) at specific altitude and azimuth angles can be calculated, thereby correcting the main errors in polarization spectroscopic observations [13]. Since the combination of altitude and azimuth angles changes with observation time and season, this process requires long-term execution.

3 Control System Equipment

The calibration unit control system can be generally divided into three parts: the host computer, the control chassis, and the drive motors. Based on requirement analysis and research for the calibration unit, ultrasonic motors and stepper motors are adopted as the drive motors for the main working components of the calibration unit. The calibration unit is installed inside the telescope's vacuum main tube and connected to the control chassis via vacuum feedthroughs. To ensure correct transmission of control commands, the control chassis should be placed beside the telescope tube. The calibration unit, analysis unit, and host computer are located in different places, not at the same work site. To enable synchronous and coordinated operation of the entire subsystem, remote wireless communication via the solar tower's local area network is used between the host computer and the control chassis, as shown in [Figure 4: see original paper]. The control of the analysis unit is similar, but since it is not in a vacuum environment and has only one motor, detailed description is not provided in this paper and can be referenced from the relevant control implementation of the calibration unit.

3.1 Ultrasonic Motor

The ultrasonic motor is a new type of driver that uses mechanical vibrations in the ultrasonic frequency domain as its driving source. Its working principle utilizes the inverse piezoelectric effect of piezoelectric materials to convert electrical energy into microscopic mechanical vibrations in the ultrasonic frequency range (above 20 kHz), and transforms these vibrations into linear or rotational motion of the moving body through resonance amplification and friction coupling. Compared with traditional motors that rely on electromagnetic effects, ultrasonic motors offer advantages such as no electromagnetic interference, good start-stop control performance, direct drive capability, and high control precision, and have been widely used in aerospace, precision instruments, and micro-electromechanical systems.

The motors driving the wave plate and polarizer rotation are PI (Physik Instrumente) M-660.55V ultrasonic motors. These motors feature a hollow rotary structure with an outer diameter of 116 mm and a central aperture diameter of 36 mm, meeting the telescope beam size requirements. Additionally, the motor thickness is 14 mm, satisfying the optical design requirements for the overall thickness of the calibration unit. The motor weighs 470 g and has a maximum rotation speed of 2 rpm. Testing revealed that when the motor's angular positioning error is 0.04%, it causes 6.25% fluctuations in measured intensity. Therefore, to reduce measurement accuracy errors introduced by intensity fluctuations, the motor's angular precision must be far less than 0.04%, meaning the angular deviation must be far less than 0.01 degrees. This ultrasonic motor is equipped with an absolute encoder with a precision of 34 μrad (0.00195°), meeting the design requirements of the calibration unit.

The manufacturer's motion controller was purchased as an accessory. This controller uses RS232 to connect with the host computer, and communication between the calibration unit control host computer and the ultrasonic motor controller is based on the manufacturer's communication protocol format and control commands.

3.2 Stepper Motor

The main working component of the calibration unit's polarization generator, composed of the wave plate, polarizer, and ultrasonic motor, is driven by a motor to achieve two modes: inserted working status and removed from the optical path. The adjustable field stop consists of three apertures with field sizes of $1'$, $3'$, and $5'$, which need to be switched according to observation requirements in practical applications. The calibration unit mechanism is installed inside the telescope's vacuum main tube, where the working environment temperature is relatively high and thermal sealing is good, creating certain heat dissipation difficulties. However, whether controlling the optical path switching or the field stop switching, the motors only work for short periods each time and drive small loads, making conventional stepper motors sufficient. Naturally, cables and lubricants must be selected according to high-temperature and vacuum environment requirements.

Stepper motors feature good dynamic response and high reliability. Based on the mechanical structure design requirements of the calibration unit, two domestic two-phase hybrid stepper motors, models 42HS4813A4 and 20HS4006A4 [14], were selected to drive corresponding equipment. The drive controller selected is the Shuoke CNC M4505A-III communication stepper control driver, which features a built-in ultra-high-performance motion controller with complete functions and excellent performance, supporting RS232 and RS485 communication. The host computer control program is written based on the Modbus ASCII communication standard, with the command format: ": device address + function code + data length + parameters + checksum \r\n".

Due to mechanical structure limitations of the calibration unit, the motion range of the optical path switching main mechanism is $(90 \pm 2)^{\circ}$. To avoid damaging the motor while ensuring normal light incidence, a feedback loop was designed to form a closed-loop numerical control system with the stepper motor and drive controller. Considering the mechanical design dimensions and system performance requirements, the JK8002D proximity sensor switch was selected, with the installation position shown in [Figure 5: see original paper]. The JK series proximity switch is a new type of automation switching device based on the Hall effect principle, characterized by high response frequency, high repeat positioning accuracy, strong anti-interference capability, high reliability, and long service life, and can be directly interfaced with PLCs.

To improve the temporal resolution of the polarization observation system, variable speed control is adopted for the optical path switching main mechanism's motion, enabling completion of insertion or removal actions within 10 seconds. The specific motion mode is as follows: when the stepper motor performs insertion motion, it starts at initial speed V_{start}, accelerates at a_1 to reach maximum speed $V_{\max}$, moves at constant speed $V_{\max}$, and to prevent mechanical collision between rotating and fixed components, the Hall switch positioning is designed with a small advance. To satisfy normal light incidence, when the controller receives the Hall switch feedback signal, it continues to move at constant speed for a fixed number of pulses to reach the predetermined position. This approach reduces cumulative errors caused by possible step loss. When the motor performs removal motion, the Hall switch feedback signal is ignored, and control follows a pattern of acceleration, constant speed, and deceleration for a fixed number of pulses. The motor motion distance (i.e., total number of pulses) was determined through multiple experiments.

For the field stop switching motor, three constant speed modes (fast, medium, and slow) are set. After selection, clicking the rotation direction enables switching.

3.3 PC Host Computer

Based on the completed hardware setup and the upper-layer communication protocols of the ultrasonic motor controller and stepper motor driver, the host computer control program was developed using Visual Studio 2015 under the C#.NET framework. The host computer system is divided into four modules: communication settings, optical path switching motor control, field stop motor control, and ultrasonic motor control, with a Windows Forms user interface developed as shown in [Figure 6: see original paper]. Users only need to select and open the corresponding motor control serial port to control the calibration unit according to actual measurement needs, combined with observation software to obtain corrections for main errors in polarization spectroscopic observations. The software reserves an OCS interface. This interface is only for current work; once the OCS is completed in the future, astronomers will not use it.

4 Wireless Remote Control Implementation

The ultrasonic and stepper motors controlling the calibration unit are connected to controllers in the control chassis via vacuum feedthroughs, and manufacturers recommend communication between the host computer and controllers through RS232 serial protocol. Since RS232 communication distance is limited, and cabling on the moving telescope and spectrograph tube requires solving cable drag issues, wireless TCP/IP is adopted as an RS232 relay. This solution simultaneously addresses both remote communication and cable drag problems.

The USR-N540 four-serial-port server produced by Youren IoT Technology features a 10/100 Mbps Ethernet port supporting Auto-MDI/MDIX, allowing both crossover and straight-through cables. It supports multiple working modes including TCP Server, TCP Client, UDP, UDP Server, and HTTPD Client. Combined with its built-in virtual serial port software (USR-VCOM), it can virtualize four independent serial ports corresponding to hardware port numbers that work independently without affecting each other, with serial baud rates ranging from 600 bps to 230.4 Kbps.

Using this serial port server as a medium, bidirectional data transmission between the host computer and each controller is achieved. In terms of physical connection, each motor controller of the calibration unit uses an RS232 interface connected to the USR-N540, which is then connected to a wireless router and accesses the 1-meter solar telescope observation building control LAN via WiFi. This realizes the physical connection between the host computer (located on the third-floor observation room) and the calibration unit.

In software, the USR-N540 and its connected wireless router are virtualized as four serial ports of the host computer. The host computer is located in the observation building control LAN, and the wireless router uses a fixed IP. After completing these configurations, control of the calibration unit becomes operations on these four serial ports, with the physical connection transparentized.

For the network architecture of the 1-meter solar telescope, the specific method to implement remote wireless control of the calibration unit is as follows: first, connect the PC to the LAN, install a router with wireless relay capability in the control chassis, then configure the router to directly connect the received WiFi signal via network cable to the Ethernet port of the serial port server, and finally use the USR-VCOM software to virtualize the required serial ports and connect them to the controller via serial cables. The PC acts as a TCP client to initiate and establish network connections, while the serial port server acts as a TCP server to monitor ports and converts TCP/IP protocol to RS232 format through its built-in protocol conversion mechanism, thereby realizing remote wireless communication between the controller and host computer via virtual serial ports.

Multiple experiments revealed that the delay caused by network communication for instruction sending and receiving averages within 20 ms, and no impact on instrument performance due to network delay was observed during observations, demonstrating the feasibility of this wireless remote control solution.

5 Conclusion

The NVST polarization observation system, particularly the calibration unit, operates in harsh environments with optical and mechanical constraints and requirements not to destroy optical path symmetry. Two major technical routes have been proposed with numerous specific implementation schemes. After several years of work, Yunnan Observatories, with support from the National Astronomical Observatories and Nanjing Institute of Astronomical Optics & Technology, completed the system installation on August 27, 2016. Figure 8: see original paper shows the installation position of the calibration unit inside the vacuum main tube, and (b) shows the connection position between the calibration unit and the control chassis outside the tube. After installation, the entire polarization observation system was tested. Results show that the calibration unit control software can accurately switch the optical path. Inputting six groups of different angular polarization states to the ultrasonic motor yields a Mueller matrix in 5-6 minutes, which can correct observation data within 15 minutes. The current system calibration relative accuracy is 1×10^{-3}. The installation and use of the calibration unit represents significant progress in the development of the 1-meter solar telescope polarization observation system, marking that the 1-meter solar telescope possesses all the hardware foundation required for high-precision polarization measurements.

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