Full-Disk Magnetic Field and Activity Monitoring Telescope: Axis System Upgrade Preprint

Authors: Chen Chuiyu, Guo Jingjing, Lin Jiaben, Deng Yuanyong

Date: 2020-05-12T11:03:41+00:00

Abstract

In astronomical observations, telescopes are required to rapidly and accurately point to target celestial objects (such as the Sun) and stably track them. This paper presents an axis system upgrade for the Full-disk Magnetic field and Activity Telescope (SMAT) at the Huairou Solar Observing Station (HSOS), wherein a 23-bit high-precision absolute encoder mounted on the servo motor shaft replaces the grating steel-tape code wheel. The solar disk center position is calculated in real time using the VSOP87 planetary theory, while a high-precision guiding system based on a large-area CCD continuously tracks the Sun and records its position. The least squares method is employed for piecewise fitting between the Sun's real-time position and the absolute encoder values, thereby establishing a pointing algorithm and achieving solar disk center pointing. Measurements demonstrate that the pointing error in the right ascension direction is approximately 36.69 , and in the declination direction approximately 21.49 , which satisfies the pointing requirements of SMAT. This method offers low cost and high compatibility, providing valuable reference for the upgrade and retrofitting of other equatorial telescopes.

Full Text

Shafting System Upgrade for the Solar Magnetism and Activity Telescope

Chen Chuiyu[1,2], Guo Jingjing[1,2], Lin Jiaben[1], Deng Yuanyong[1,2]

[1]Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
Email: cychen@nao.cas.cn

Abstract

In astronomical observations, telescopes must be capable of rapidly and accurately pointing to target celestial objects (such as the Sun) and tracking them stably. This paper presents a shafting system upgrade for the Solar Magnetism and Activity Telescope (SMAT) at the Huairou Solar Observing Station (HSOS). The upgrade replaces the grating steel tape encoder with a 23-bit high-precision absolute encoder mounted directly on the servo motor shaft. The VSOP87 planetary theory is employed to calculate the solar disk center position in real time, while a high-precision guiding system based on a large-area CCD continuously tracks the Sun and records its position. Using the least squares method, we perform piecewise fitting between the Sun's real-time position and the absolute encoder values to establish a pointing algorithm and achieve solar disk center pointing. Field measurements demonstrate a pointing error of approximately 36.69 in right ascension and 21.49 in declination, meeting SMAT's pointing requirements. This method offers low cost, high compatibility, and serves as a valuable reference for upgrading other equatorial telescopes.

Keywords: pointing control, pointing error, shafting upgrade, solar observation, equatorial telescope

Introduction

The Huairou Solar Observing Station (HSOS) is a renowned research facility for solar magnetic field and velocity field observations, enjoying high prestige in the international solar physics community. The Solar Magnetism and Activity Telescope (SMAT) is one of HSOS's key observational instruments [Figure 1: see original paper], supported by major projects from the national space weather agency. SMAT achieved first light in December 2005 and passed acceptance testing for routine observations in May 2006 [1]. The telescope consists primarily of an Hα telescope and a full-disk vector magnetic field telescope, designed to study the dynamic processes and triggering mechanisms of solar eruptions through observations of large-scale photospheric vector magnetic field evolution and chromospheric activity phenomena [2]. After more than 14 years of operation, the shafting system requires renovation and upgrading to ensure long-term stable observations and improve observational efficiency.

SMAT is an equatorial telescope with two telescope tubes on its mount: a full-disk solar magnetic field telescope and a full-disk solar Hα telescope. Key design parameters are shown in Table 1 . The original design employed a grating steel tape encoder as the position detection element, based on which a corresponding position closed-loop tracking system was constructed [3]. In 2012, the encoder failed, making telescope tracking and guiding impossible. Without automatic pointing capability, observers had to manually control the telescope toward the Sun using a joystick based on experience, resulting in low pointing accuracy and inefficiency. This study addresses SMAT's shafting upgrade by replacing the grating steel tape encoder with a high-precision shaft-mounted encoder, achieving position detection at lower cost and with greater compatibility. Using the shaft encoder as a feedback mechanism and leveraging a high-precision guiding system to track the Sun, we record the Sun's real-time position and encoder values to establish a telescope coordinate system, implement pointing functionality, and enable centering of the solar disk during normal observation periods, thereby enhancing telescope observation efficiency.

1. Basic Principles of Solar Telescope Pointing and Algorithm Design

The pointing control system is a critical subsystem for telescope shafting motion control, enabling automatic alignment of the telescope with the Sun without manual adjustment by observers. As shown in Figure 2 [Figure 2: see original paper], the process first requires establishing models for the Sun's real-time position and the telescope's real-time position. Based on these position models, the difference between telescope position and solar position is calculated. This position difference is then converted to pulse quantities for the motion control system, which are sent to the shafting control system to drive the telescope toward the Sun. The pointing control system must rapidly and accurately direct the telescope to the observation target. Considering SMAT's actual conditions, the pointing accuracy specification is set at 1 arcminute.

1.1 Calculation of Solar Disk Center Coordinates Pointing to the solar disk center requires first calculating its real-time coordinates. This paper adopts the VSOP87 planetary theory proposed by P. Bretagnon and G. Francou [5], which can accurately calculate the positional distribution of the eight planets in the solar system relative to the Sun at any given moment. The method features relatively simple computation with errors within 2 [6].

Based on the Earth's periodic term coefficients from this theory, we can calculate:

In equation (1), represents the number of millennia from the current Julian day to J2000.0, is the heliocentric ecliptic longitude, b is the heliocentric ecliptic latitude, r is the heliocentric distance, and and R are periodic term coefficients.

In equation (2), after converting heliocentric ecliptic longitude and latitude to geocentric coordinates, nutation correction and aberration are considered to obtain apparent ecliptic longitude L and apparent ecliptic latitude B. From L and B, we can calculate apparent right ascension and declination:

In equation (3), α is the apparent right ascension, is the apparent declination, and is the true obliquity of the ecliptic. From α, we can calculate the hour angle t:

In equation (4), is the sidereal time at 0h local mean time, T is the current Beijing time, and $\Delta T = 120° - \lambda$ is the difference between the local geographic longitude and 120° east longitude, expressed in hours, minutes, and seconds.

Through equation (5), equatorial coordinates can be transformed to horizontal coordinates. Equations (6) and (7) derive azimuth A and altitude H from apparent declination and hour angle :

In summary, the solar disk center coordinates can be calculated in real time using the above formulas. Figure 3 [Figure 3: see original paper] shows the variation of solar azimuth and altitude at different solar terms at the Huairou Solar Observing Station.

1.2 Establishment of Telescope Coordinates The shaft-mounted encoder enables measurement of motor rotation. As the motor drives the telescope mount, the encoder reflects the telescope's motion in right ascension and declination [7]. Through calibration, a correspondence between encoder values and telescope rotation angles in right ascension and declination can be established, allowing telescope coordinates to be built from encoder readings and providing specific information about the telescope's current position.

Using the telescope's built-in graduated circles and gyroscope to measure encoder values and actual telescope positions, we obtain Tables 2 and 3 . Multi-turn count refers to the number of motor rotations (how many complete turns the motor has made), single-turn position refers to the subdivided position after rotation (with 23-bit resolution, each full turn is subdivided into 6,388,608 positions), and total count = multi-turn count × 6,388,608 + single-turn position.

Table 2 Encoder values for different right ascension (hour angle)

Right Ascension (Hour Angle)	Azimuth Total Count
06:00	
08:00	
10:00	
12:00	
14:00	
16:00	
18:00	

Converting hour angle to degrees (with north as 0°, clockwise positive) and performing linear fitting between hour angle and corresponding azimuth total count yields:

where = 132,960,829.93 is the right ascension-to-count conversion coefficient, and = 525,874,647,886.86 is the intercept related to the selected zero position. The correlation coefficient after fitting is $R = 0.99998812$.

During initial debugging, we found that due to inherent shafting errors in the telescope, the relationship between hour angle and count could not be well fitted with limited data when the telescope crossed the balance position. To further improve pointing accuracy, we employed the method proposed by Guo Jingjing et al. [4], which uses a large-area CCD to capture full-disk Hα solar images from the main telescope for high-precision guiding, tracking the Sun and recording solar position and encoder values every second. Through all-day tracking, we established piecewise fitting relationships using the least squares method.

Right ascension:

where is the right ascension-to-count conversion coefficient and is the intercept related to the selected zero position. Fitting yields:

The correlation coefficient after piecewise fitting using guiding data improved by two orders of magnitude compared to the original.

Table 3 Encoder values for different declination

Declination (degrees)	Altitude Total Count

Converting declination parameters to degrees (with horizontal as 0°, upward positive) and performing linear fitting between angle and corresponding altitude total count yields:

where = -398,882,489.78 is the declination-to-count conversion coefficient, and = 549,807,597,273.57 is related to the selected zero position. The correlation coefficient after fitting is $R = 0.99998812$.

1.3 Basic Pointing Algorithm By reading time and geographic location information, the solar disk center coordinates are calculated in real time. The telescope position is computed using the shaft-mounted encoder, and the position difference between telescope and solar disk center serves as input. The controller converts this difference into corresponding command signals sent to the driver according to the following formula. The driver sends pulse signals to the servo motor, which drives the telescope shafting system to point toward the Sun.

Driver pulse count = (Solar disk center right ascension (declination) corresponding total single-turn count - Telescope current right ascension (declination) total single-turn count) × Motor pulses per single-turn output

Based on the above principles and algorithm research, real-time calculation of solar position and telescope actual position can be achieved. The next step involves hardware and software transformation and upgrading of SMAT, including hardware selection, construction, and debugging according to the telescope's actual conditions, as well as implementing the algorithm in control software to realize algorithm functionality through integration of hardware and software platforms.

2. Hardware and Software System Upgrade

In 2012, SMAT's grating steel tape encoder failed, and the shafting motor, being relatively old, could not read encoder values, leaving the telescope without position detection capability. Reinstalling a grating encoder would require custom design based on the telescope structure, involving adjustments to the telescope's opto-mechanical configuration and potential recalibration of the shafting system after replacement. Additionally, developing a corresponding data acquisition system compatible with the telescope control software would require substantial manpower and resources. To reduce costs and improve compatibility, we decided to replace the original motor with a servo motor equipped with a 23-bit absolute encoder and integrate the controller and driver to create a new shafting system control box, achieving hardware transformation. Encoder data acquisition and pointing functions were integrated into the HSOS full-disk solar telescope control software, enabling comprehensive control of the shafting system through this software.

2.1 Hardware System Transformation Before the upgrade, SMAT used a Mitsubishi HC-SFS52 motor with a rated power of 750W and a 17-bit incremental encoder with a resolution of 131,072 p/rev. To achieve higher-precision position detection and establish a stable telescope coordinate system, the motor was replaced with a Panasonic A6 servo motor (model MSMF082L1U2U2M) with driver model MCDLT35SF. This motor features a 23-bit shaft-mounted absolute encoder with a resolution of 8,388,608 p/rev. Unlike incremental encoders, absolute encoders determine position through unique output codes for each location within one revolution [8]. When forming an absolute system, absolute encoders do not require homing upon power-on, enabling stable telescope coordinate establishment—crucial for pointing functionality. Absolute encoders with independent power supplies also retain position information after power loss or accidental displacement.

The encoder acquisition system is integrated within the servo motor, and the host controller can connect to both right ascension and declination motors simultaneously via RS485 or RS232 communication, reading position information as serial data to obtain absolute position information for both axes after processing [9]. Compared with grating steel tape encoders, shaft-mounted encoders require no custom design, utilize mature universal products at lower cost, involve simpler data acquisition without additional grating read heads or data acquisition cards, and minimize concerns about installation precision and system calibration. Another consideration is that direct motor replacement does not involve telescope structural displacement or require shafting recalibration.

A new shafting system control box was constructed (Figure 4 [Figure 4: see original paper]), using an ADT-8860 programmable controller from ADTECH. This controller enables servo motor control, encoder value reading, and provides independent hard limit and joystick control interfaces for functionality without software intervention.

2.2 Software System Upgrade The Hα telescope observation software (Figure 5 [Figure 5: see original paper]) was developed using object-oriented C++ language under the VS2010 platform. Based on the original HSOS full-disk telescope control system, real-time reading and display of right ascension and declination encoder single-turn/multi-turn values were implemented. Functions such as "azimuth pointing" and "altitude pointing" were added to achieve real-time pointing to the solar disk center, with the capability to point to any position within the telescope shafting's allowable range by inputting hour angle and declination parameters.

3. Test Results

On January 4, 2020, pointing functionality was tested on SMAT. A reference image was preset (Figure 6 [Figure 6: see original paper]), and pointing was performed every 15 minutes from 08:55 to 15:55, with full-disk Hα solar images retained after each pointing. Figure 7 [Figure 7: see original paper] shows Hα solar images captured at 60-minute intervals. Using a solar image centroid and radius detection algorithm based on Hough transform, images were analyzed and compared with the reference image to calculate errors. Throughout the day, the data in Table 4 were obtained.

The reference image's center coordinates are (1207.0, 1211.0). The Hα solar image diameter on that day was R 2296.593084 pixels, and the solar apparent diameter at noon was $R = 32$ 32.01 , yielding a scale of approximately 1 pixel 0.849959 in Figure 6.

Table 4 Data at different times after pointing

Time	Center RA Coordinate (pixel)	RA Offset (pixel)	Center Dec Coordinate (pixel)	Dec Offset (pixel)	Radius (pixel)
08:55					
09:10					
…					
15:55					

Figure 8 [Figure 8: see original paper] shows the pointing deviation in right ascension and declination relative to the reference image. Using formula (8), the standard deviation of pointing can be calculated:

After conversion, the pointing error in right ascension is approximately 36.69 , and in declination approximately 21.49 , with pointing accuracy ≤ 1 , meeting the specified requirements.

3.2 Conclusion Through the shafting system upgrade of SMAT, this study implements a control method that uses a high-precision guiding system to track the Sun, records solar real-time position and absolute encoder values, and establishes a pointing algorithm through piecewise linear fitting. This method features low cost, strong portability, and high compatibility with equatorial telescope shafting systems, making it suitable for upgrading telescopes with long service lives. Field testing demonstrates pointing accuracy better than 1 , fulfilling functional requirements and successfully bringing the solar image into the field of view for guiding.

It should be noted that while current work meets SMAT's operational needs, there remains room for further improvement. Multiple factors may contribute to pointing errors: inherent telescope shafting errors, pointing algorithm errors, atmospheric refraction, and even the solar image centroid and radius detection algorithm. Future work will require quantitative analysis to establish error models for further pointing accuracy improvement.

Acknowledgments

We thank HSOS observers Wang Guoping and Jing Shuai for their assistance and support during this research, and Xun Hui, Yang Xiao, Zhang Xinwei, and Tong Liyue for their help and valuable suggestions. We also thank Wang Qiang for providing the solar image centroid and radius detection algorithm based on Hough transform. This research was funded by the National Natural Science Foundation of China (11427901, 11427803), the Strategic Priority Research Program of the Chinese Academy of Sciences (Class A) (XDA15320102), the CAS Key Technology Talent Program, and the NAOC Platform Technology Project.

References

[1] Lin Jiaben, Shen Yangbin, Zhu Xiaoming, Deng Yuanyong, Zeng Zhen. Automated observation system for full-disk magnetic field at Huairou Solar Observing Station[J]. Astronomical Research & Technology, 2013, 10(04): 392-396.

[2] Solar Magnetism and the Activity Telescope at HSOS[J]. Chinese Journal of Astronomy and Astrophysics, 2007(02): 281-288.

[3] Wu Chunhui, Zhu Qingsheng, Zhou Xiaojun. Automatic tracking and guiding method for full-disk solar optical and magnetic field telescope[J]. Astronomical Research & Technology, 2007(02): 147-152+146.

[4] Guo Jingjing, Yang Yunfei, Feng Song, Ji Kaifan, Lin Jiaben, Zeng Zhen, Wang Bingxiang. High-precision guiding method for solar telescopes[J]. Chinese Science Bulletin, 2016, 61(10): 1112-1120.

[5] BRETAGNON, FRANCOU. Planetary theories in rectangular and spherical variables. VSOP 87 solutions[J]. 1988, 202(1-2): 309-315.

[6] Liu Guangqian. Development of control system for one-meter infrared solar telescope[D]. 2011.

[7] Yan Lingjie. Research on boresight pointing and prediction technology for photoelectric telescope[D]. University of Chinese Academy of Sciences (Institute of Optoelectronics, Chinese Academy of Sciences), 2019.

[8] Cheng Xiaoli, Xie Jianying, Wang Lin. Application of absolute encoder in motor positioning[J]. Control Engineering, 2007, 14(5): 548-550.

[9] Ke Zibo, Yan Lei, Wang Dongguang. Development and verification of atmospheric polarization neutral point remote sensing observation system[J]. Imaging Science and Photochemistry, 2019, 37(03): 85.

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