Large-aperture Telescope Tracking Control Based on Time-synchronization Strategy (Postprint)

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Abstract

A time-synchronization strategy for packetized transmission of target position about a large-aperture telescope observation control system has been proposed in this study. Compared with the existing telescope tracking strategy, the target position packing and sending strategy based on the time synchronization method proposed in this paper has the advantages of high stability and reliability. First, the telescope tracking observation control method was elaborated in this paper, including the motion pattern during telescope tracking. Then, the strategy for packetizes transmission of target positions based on time-synchronization is established and lists the detailed steps. Finally, the performance of the tracking strategy is verified using the 2.5 m telescope for the simulated uniform speed star and the blind-tracking fixed star HIP 31216, respectively. The test results show that the accuracy root mean square of the tracking strategy proposed in this paper is less than 002 at 30 minutes, and the performance is much better than the design requirement of 03. The most important advantage of this tracking strategy is that the telescope can guarantee normal tracking for a certain period of time even if the hardware or software of the host computer is abnormal.

Full Text

Preamble

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Large-aperture Telescope Tracking Control Based on Time-synchronization Strategy

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Abstract

This study proposes a time-synchronization strategy for packetized transmission of target positions in large-aperture telescope observation control systems. Compared with existing telescope tracking strategies, the target position packing and sending strategy based on the time synchronization method proposed in this paper offers higher stability and reliability. First, the telescope tracking observation control method is elaborated, including the motion pattern during telescope tracking. Then, the strategy for packetized transmission of target positions based on time synchronization is established, and detailed steps are listed. Finally, the performance of the tracking strategy is verified using a 2.5 m telescope for both a simulated uniform-speed star and the blind-tracking of fixed star HIP 31216. The test results show that the root mean square accuracy of the tracking strategy proposed in this paper is less than 0 02 at 30 minutes, which is much better than the design requirement of 0 3. The most important advantage of this tracking strategy is that the telescope can guarantee normal tracking for a certain period of time even if the hardware or software of the host computer is abnormal.

Key words: miscellaneous -telescopes -methods: observational -methods: analytical

1. Introduction

Telescopes have played a significant role in advancing our knowledge of astronomy and physics, enabling us to study celestial objects such as planets, stars, galaxies, and other cosmic phenomena that were once beyond our reach. In recent years, technological advancements have led to the development of more powerful and sophisticated telescopes, such as the James Webb Space Telescope [?], Thirty Meter Telescope (TMT) [?], and European Extremely Large Telescope (E-ELT) [?].

Telescope control systems are hardware and software programs that manage various aspects of telescope operation, including pointing, tracking, and focusing. These systems are designed to automate tasks that would otherwise be time-consuming or impossible for astronomers to perform manually. Since telescopes are often located in remote locations with harsh weather conditions and challenging terrain, control systems are essential as they allow astronomers to operate telescopes from distant locations. As technology continues to advance, we can expect telescope control systems to become even more sophisticated, enabling us to explore the universe with greater precision and accuracy.

A reliable software platform can effectively improve operational efficiency, such as the core Flight System (cFS) proposed by McComas [?, ?], which researchers are attempting to adapt for telescope control software in both ground-based and space-based observations [?]. The software system of the TMT consists of a software infrastructure called TMT Common Software (CSW) [?] that interacts with various subsystems to satisfy telescope functions, such as the pointing and tracking system and the Alignment and Phasing System (APS) [?].

The performance of telescope control systems is directly related to the robustness of the control loop and the ability to avoid resonance excitation. E-ELT telescopes have defined new performance requirements for all engineering fields involved in telescope design and implementation [?, ?]. To achieve reliable observation, Keck I and Keck II have implemented the Telescope Control System Upgrade (TCSU) project, which includes mechanical, electrical, and software components [?]. To improve the tracking performance of the Green Bank Telescope (GBT) [?], a new method for identifying correction coefficients for encoder interpolation error was developed [?], which reduced the root mean square (rms) tracking error from 0 68 to 0 21. A quaternion-based solution using low-cost hardware has been proposed for rapid telescope pointing calibration [?], presenting a quaternion-based pointing model for use with a star camera.

Model calibration to improve pointing accuracy is a commonly used method. The Imaging Atmospheric Cherenkov Telescope (IACT) improves tracking accuracy through pointing corrections made by a CCD camera capturing a Cherenkov camera with LEDs and an observational light source in the sky [?]. GBT has developed a specialized pointing model to correct inaccuracies due to gravitational flexure, thermal deformation, azimuth track tilt, and offset errors [?]. The Daniel K. Inouye Solar Telescope (DKIST) [?] and the Airborne Lunar Spectral Irradiance Mission (ALSIM) obtain lunar pointing with similarly improved accuracy through modeling [?]. The quaternion-based pointing modeling method is an effective way to improve the pointing accuracy of telescope control systems [?]. In addition to model correction methods, iterative learning algorithms can also address local pointing model inaccuracies and dynamic effects during tracking [?]. Improving telescope system accuracy with well-performing control models is another common approach; for example, acceleration feedback control is effective in dealing with wind disturbances, nonlinear disturbances, and other unknown disturbances [?].

In addition to software reliability, many other factors affect ground-based telescope astronomical observations, such as distortions and instabilities [?], water vapor [?], seeing [?], and site conditions [?]. Beyond enhancing observation performance, new processing methods are also available, such as digital tracking for asteroid searches that greatly increases telescope sensitivity to faint unknown asteroids [?]. Time synchronization strategies have wider applications in astronomical observation and telescope control. The Main Atmospheric Cherenkov Experiment (MACE) telescope uses various subsystems synchronized by a highly stable temperature-controlled oscillator clock for the Telescope drive Control Unit (TCU), an active mirror calibration system, camera electronics, and signal processing based on the Global Positioning System (GPS) [?]. The GTC telescope (Gran Telescopio CANARIAS) also plans to apply time synchronization methods to its distributed subsystems to improve system performance [?]. The Cherenkov Telescope Array (CTA) improves the efficiency of acquiring high-energy gamma rays by synchronizing precise timestamps to distributed devices [?]. Additionally, the concept of time synchronization has been introduced in telescopes for real-time tracking of satellites and satellite laser ranging to reduce latency and data loss [?].

This paper proposes a telescope tracking control method based on a time-synchronization strategy to achieve target position packing and transmission, which is more stable and fault-tolerant, and can ensure smooth astronomical observation even when the TCS (Telescope Control System) and OCS (Observation Control System) host computers are abnormal. The method proposed in this paper provides a new telescope tracking control strategy with higher tracking accuracy, greater stability, and enhanced fault tolerance. The lack of a large-aperture optical/infrared telescope has seriously affected the development of Chinese astronomy, and the results of this research can provide technical support for the next generation of 10 m class telescopes in China [?].

The main strategies to improve telescope tracking accuracy are: reducing the pointing tracking error of the control system itself, improving the accuracy of the pointing model, and including a guide star system. This paper focuses on reducing the pointing tracking error of the control system itself to improve telescope tracking accuracy and enhance reliability. The problem addressed in this paper is implementing a tracking control strategy based on the time synchronization method for target position packing and sending to improve the accuracy and reliability of telescope tracking.

The novelties of this study are twofold:

1. The time synchronization strategy is a prerequisite for this research method, which utilizes a time server to synchronize the time of the OCS host computer, TCS host computer, and controller of the telescope control system with millisecond-level accuracy.
2. The target star position is packaged and sent to the controller. This research method can guarantee normal operation of telescope astronomical

observation in case of hardware or software failure of OCS and TCS computers, offering high reliability and fault tolerance.

The rest of this paper is organized as follows: Section 2 presents the concept of the telescope tracking observation control system, including the drive system and tracking strategy. Section 3 provides the theoretical background and implementation of the method proposed in this paper. Section 4 describes the experiments developed according to the method in Section 3. Section 5 summarizes the entire paper and details further research plans.

2. Telescope Tracking Observation Control

To achieve high-quality tracking observation of a target celestial body, the telescope needs to coordinate the azimuth, altitude, and derotator axes. Additionally, to capture clearer images, systems such as focus adjustment, active optics, and adaptive optics are also involved. This paper focuses specifically on how the telescope achieves precise tracking of the target celestial body.

2.1. Notion of Telescope Drive System

The drive system is the hardware and software foundation for achieving telescope tracking and observation, which includes the TCS host computer, controller, actuators, sensors, and software processing programs. The control method adopts a multi-closed-loop control strategy, in which the main control computer sends instructions to the controller to drive the actuators, enabling coordinated motion of the azimuth, altitude, derotator, focusing, M2/M3 adjustment, filter, and other mechanisms. Encoders, resolvers, and length gauges provide feedback information such as position and speed. The schematic diagram of the telescope drive system is shown in Figure 1 [Figure 1: see original paper].

2.2. Telescope Tracking Observation Strategy

The essence of tracking and observing a target star through a telescope from standstill is a pursuit problem. First, the Telescope Control System (TCS) calculates the position of the target star over the following period and converts it into angular information for the three axes of telescope azimuth, altitude, and rotation based on celestial coordinates. Then, the telescope moves from its current coordinates to the target star position in a high-speed pointing mode. However, since the target star is also in motion during the telescope’ s pointing process, the telescope must continuously adjust its pointing position. This process requires several iterations to complete, ensuring a perfect encounter between the telescope and the target star at a specific time, before finally entering the low-speed tracking phase. The schematic diagram of the telescope tracking observation is shown in Figure 2 [Figure 2: see original paper].

2.3. Motion Patterns during Telescope Tracking

In this paper, the telescope tracking observation process is divided into two parts: high-speed pointing and low-speed tracking. At the beginning of telescope design, the maximum speed and acceleration during the pointing movement process, as well as the tracking error and other parameter indicators during the tracking process, are determined. In this paper, the maximum pointing speed is assumed to be Vmax (arcsec s^{-1}) and the acceleration is assumed to be apointing (arcsec s^{-2}). The tracking speed is determined by the running speed of the target star.

The maximum velocity is one of the most important indicators of telescope design and is determined at the beginning of development. It is related to the rotational inertia of the telescope structure, motor selection, and the size of the zenith blind zone. On the one hand, too small a maximum speed will lead to the inability to track targets near the zenith blind zone. On the other hand, too small a maximum speed will result in the telescope’ s response speed being too slow, making zenith zone switching too time-consuming.

The high-speed pointing motion mode can be divided into two cases depending on whether the maximum speed is reached. The two motion modes are determined by the critical distance between the telescope’ s current position and the target star’ s position. This critical distance can be calculated from the maximum pointing velocity Vmax and acceleration apointing, and is set to S0. That is, where acceleration time = ta. So, S0 can be written as follows:

$$S_0 = \frac{V_{\max}^2}{a_{\text{pointing}}}$$

Motion mode I: The pointing velocity reaches the maximum speed, which means the pointing movement process is accelerated first, followed by uniform speed, and then decelerated. In this case, the current position of the telescope is greater than S0 from the target star position. If the distance between the current position of the telescope and the position of the target star is Sx, the telescope pointing motion time Tx (seconds) can be calculated.

Then, we can get the uniform motion time tu:

$$t_u = \frac{S_x - S_0}{V_{\max}}$$

So, the telescope pointing motion time Tx = 2 × ta + tu can be written as follows:

$$T_x = \frac{V_{\max}}{a_{\text{pointing}}} + \frac{S_x - S_0}{V_{\max}}$$

Motion mode II: The pointing velocity does not reach the maximum speed, which means the pointing movement process is accelerated first and then decelerated. In this case, the current position of the telescope is less than or equal to S0 from the target star position. In this motion mode, the telescope pointing motion time Tx (seconds) can be calculated.

And then, we can get the uniform motion time tx:

$$t_x = \sqrt{\frac{S_x}{a_{\text{pointing}}}}$$

So, the telescope pointing motion time Tx = 2 × tx can be written as follows:

$$T_x = 2\sqrt{\frac{S_x}{a_{\text{pointing}}}}$$

The schematic diagrams of motion mode 1 and motion mode 2 are shown in Figure 3 [Figure 3: see original paper].

3. Time-Synchronization-Based Tracking Method

3.1. Time Synchronization Strategy

The time synchronization strategy is the basis for the precise tracking observation method proposed in this paper. The time server can provide high-precision time services externally, such as the American GPS, the Chinese Beidou Navigation Satellite System (BDS), and atomic clocks. The calculation of the target star’ s position, determination of the telescope pointing, and transmission of control instructions all rely on accurate time. Time servers regularly synchronize and calibrate the host computer and controller time of the telescope control system, with error accuracy maintained at the millisecond level.

The time server, host computer, and controller are connected via a fiber optic network through a Gigabit industrial Ethernet switch so that they work under the same Local Area Network (LAN). The time server provides Network Time Protocol (NTP) service to the host computer and controller. The schematic diagram of the time synchronization strategy is shown in Figure 4 [Figure 4: see original paper].

3.2. Target Location Packing and Sending

Target star position packing and sending are important technical means for the telescope to realize the precise tracking observation method proposed in this paper, which is also based on the time synchronization strategy. The steps are as follows:

Step 1: For the observation of a known target star, the TCS host computer calculates the position of the target star and generates a catalog with a sampling interval of 100 ms. Each group of data contains time, azimuth position, altitude position, and derotation position, recorded as Time, AZ_{Position}, ALT_{Position}, and Dero_{Position}.

Step 2: The TCS host computer program reads the time of the first line of the star table, defined as TBaseLine1 (millisecond), and assigns the position data of the table to the variables PStartAddressNum to PStartAddressNum+N−1 in turn, where StartAddressNum is the P variable register start code, and the values of N and StartAddressNum are determined by the total number of controller registers. Then the above data is defined as group A and packaged and sent to the controller of the system.

Step 3: Same as step 2, the TCS host computer program assigns the (N+1)th to (2×N)th row of the star table position data to variables PStartAddressNum+N to PStartAddressNum+2×N−1 in turn, then defines the above data as group B and sends it to the controller of the system in package.

Step 4: Start the controller motion program while executing step 3, take the current time of the controller system, defined as TCurrent (millisecond), and calculate the time difference between the current system time and the first row of the star table time, defined as TDifference (millisecond). So, TDifference = TCurrent − TBaseLine1. The number of rows in the star table at the current position of the target is defined as PointLine. That is:

$$\text{PointLine} = \text{int}\left(\frac{T_{\text{Difference}}}{100}\right) + 1$$

where int() represents an integer function, commonly used in programming and mathematical expressions.

Step 5: The telescope pointing target location is defined as PointTarget, which is given by Equation (9):

$$\text{PointTarget} = P_{\text{StartAddressNum+PointLine}}$$

The current position of the telescope is defined as CurrentPosition and is known. That is, the current distance between target and telescope is Sx = |PointTarget − CurrentPosition|. When Sx > S0, motion mode I is executed; otherwise, motion mode II is executed. The pointing motion time of the telescope in different motion modes can be determined from Equations (4) and (7). Update the value of PointLine, that is, PointLine = int(TDifference/100) + 1 + int(Tx/100). The value of PointTarget is also updated.

Step 6: Since the target star is not stationary during the telescope' s pointing process and its velocity is not uniform, when the telescope points and moves to the target star position calculated in Step 5, the target star is no longer at that position. Theoretically, the pursuit problem requires repeated iterations of step 5 to complete, but countless iterations are not possible in engineering applications, so about 3 times is usually sufficient. However, unlimited iterations are not possible in engineering applications, and the telescope has a certain field of view, so the number of iterations usually depends on the specific situation.

Step 7: From steps 1 to 6, the precise position that the telescope should point to can be calculated, and the controller drives the telescope to point to the target. After completing the tracking of group A, it automatically switches to group B, then updates group A while tracking group B, thus realizing the alternate tracking of two groups of data.

The schematic diagram of telescope tracking for target position packaging transmission is shown in Figure 5 [Figure 5: see original paper].

4. Performance Evaluation

4.1. 2.5 m Telescope Platform

The above content verifies the feasibility and advantages of the target localization packaging and tracking method based on time synchronization strategy from the perspective of qualitative analysis. This section provides quantitative proof.

A Chinese 2.5 m altitude-azimuth telescope in the commissioning stage serves as the verification platform for this study, primarily used for observations of known target objects such as fixed stars and satellites. The azimuth axis inertia of the telescope is 12,400 $\text{kg} \cdot \text{m}^2$, and the altitude axis inertia is 32,000 $\text{kg} \cdot \text{m}^2$ during full load operation. The current state inertia is about 90% of the full load, which means the current test can represent the performance of the telescope during observations. The simulation and physical diagram of the 2.5 m telescope are shown in Figure 6 [Figure 6: see original paper].

The control system of the telescope is mainly composed of a host computer, controller, driver, motor, and position feedback encoder. The resolution of the encoder is directly related to the tracking accuracy of the telescope. The 2.5 m telescope of this research platform adopts a 29-bit absolute encoder with a resolution up to 0 0024, whereas the design specification for telescope tracking accuracy is rms $\leq$ 0 3 with no guide closed loop, which is far more than adequate for the requirements.

4.2. Data Collection and Analysis

The 2.5 m optical telescope is currently in the commissioning phase. The frame of the azimuth axis and the main mirror compartment of the altitude axis have been installed, which can realize simulation tracking of the target sky area.

The performance of the proposed tracking strategy is verified by using the 2.5 m telescope to track a simulated uniform-speed star and fixed star HIP 31216, respectively. The trajectory of the simulated uniform-speed star over a one-hour period is shown in Figure 7 [Figure 7: see original paper], with the telescope tracking at 15 s^{-1} for both azimuth and altitude. The position of star HIP 31216 in the J2000 coordinate system is R.A.: 6h 32m 54 23, decl.: 7° 59 58 6, and its trajectory over a one-hour period is shown in Figure 8 [Figure 8: see original paper].

The purpose of tracking tests with the telescope on a simulated uniform-speed star is to examine the performance of the telescope under long periods of uniform-speed operation. The velocity of the simulated star in azimuth and altitude directions is 15 s^{-1}, the starting position of the star table is AZ: 40° 00 00 , ALT: 40° 00 00 , and the current position of the telescope is at AZ: 10° 00 00 , ALT: 20° 00 00 . The telescope followed the simulated star for up to 30 minutes, and the following errors in azimuth and altitude are shown in Figures 9 [Figure 9: see original paper] and 10 [Figure 10: see original paper].

The tracking error of the telescope drive system can be determined by combining the tracking errors of azimuth and altitude using the coordinate system conversion equation, as shown in Equation (13):

$$\mathrm{Rms}_{\mathrm{Telescope}} = \sqrt{(\mathrm{Rms}_{\mathrm{AZ}} \cos(\mathrm{Target}_{\mathrm{ALT}}))^2 + (\mathrm{Rms}_{\mathrm{ALT}})^2}$$

In Equation (13), RmsTelescope represents the tracking error of the telescope drive system, while RmsAZ and RmsALT represent the following error of azimuth and altitude, respectively. TargetALT denotes the target position of altitude. The tracking error of the telescope drive system following the simulated star is shown in Figure 11 [Figure 11: see original paper].

To verify the real tracking performance of the tracking strategy proposed in this paper, fixed star HIP 31216 is randomly selected with the help of Stellarium software and blindly followed by the 2.5 m telescope. The detailed information of star HIP 31216 is shown in Table 1 .

The telescope followed HIP 31216 for up to 30 minutes, and the following errors in azimuth and altitude are shown in Figures 12 [Figure 12: see original paper] and 13 [Figure 13: see original paper], and the tracking error of the telescope drive system is shown in Figure 14 [Figure 14: see original paper].

The results of the quantitative calculations of the telescope azimuth, altitude, and integrated tracking error are shown in Table 2 .

4.3. Explanation of Results

The design index of the tracking error rms for the 2.5 m telescope used for testing is 0 3 with no guide closed loop. From the above results, it is clear that the error rms of the tracking strategy proposed in this paper is much better than the index requirement. The telescope tracking program stores 9000 position data points in each group, meaning the host computer sends 9000 position data points to the controller at once. This behavior enables the telescope to maintain 15-30 minutes of normal observation even in the case of software or hardware failure of the host computer. This case was also verified during the test, which represents the biggest advantage of the tracking strategy proposed in this paper.

4.4. Advantages of this Tracking Strategy

Compared with existing tracking strategies, the method based on time synchronization to achieve packetized delivery of target locations offers obvious advantages:

1. The tracking method proposed in this paper can avoid frequent error corrections in the telescope tracking process, which directly improves tracking accuracy and indirectly improves image quality.
2. The tracking method proposed in this paper can reduce the number of interactions between the host computer and controller, thereby reducing the probability of telescope tracking failure caused by communication abnormalities.
3. The program can still ensure normal tracking for a certain period of time in the case of hardware or software crash of the TCS host computer, which gains time for the TCS computer to restart, thus providing high fault tolerance and robustness.

5. Discussion and Conclusion

Based on the above study, it can be concluded that the tracking strategy based on time-synchronized packetized sending of target positions effectively reduces the frequency of interaction between the host computer and the controller, and guarantees tracking observation for a specific time period even in the case of an abnormal host computer. The new tracking strategy proposed in this paper is of great significance for improving the observational reliability and efficiency of telescopes.

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