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Reliability Improvement Strategies for Telescope Control Systems

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Abstract

The telescope drive control system provides essential power support for the successful execution of astronomical observations, and its reliability directly impacts the efficiency of these observations. This paper focuses on strategies for enhancing the reliability of the telescope drive control system, proposing a comprehensive and multidimensional reliability improvement solution. The study examines mechanisms for enhancing reliability from three perspectives: expected fault diagnosis, unanticipated state identification, and reliability optimization during the design phase. For each of these aspects, specific reliability enhancement solutions are proposed, including a fault diagnosis and self-healing expert system, a generic process model for unanticipated state identification, and an optimized tracking control strategy under timestamp synchronization. Furthermore, the paper demonstrates the feasibility of these solutions from the three aforementioned perspectives, providing a clear direction for the development of reliability enhancement strategies for telescopes.

Unified Astronomy Thesaurus concepts: Telescopes (1689); Ground telescopes (687); Astronomy data analysis (1858); Computational methods (1965)

1. Introduction

The drive control system serves as the power support for the normal operation of the telescope and is essential for ensuring the smooth conduct of astronomical observations. The effective operational duration is a key indicator for evaluating the efficiency of the telescope, and the reliability of the drive system is directly related to the observational efficiency. Therefore, researching mechanisms for enhancing the reliability of the telescope's drive system is of significant importance. This paper investigates various factors that influence the reliability of the telescope drive control system, analyzing the constraints on its reliability improvement from different perspectives and formulating potential solutions.

Telescopes are often situated in high-altitude, cold, and remote areas, such as plateau regions, polar regions, and even in space. As the operational conditions become more demanding, the reliability requirements for the telescope drive system increase correspondingly. Developing mechanisms to enhance the operational reliability of the drive control system tailored to different environments is crucial for improving the efficiency of telescope operations. The Lenghu Astronomical Observation Base in China, located at an altitude of 4200 m, offers world-class astronomical observation conditions, comparable to renowned observatories such as the Mauna Kea Observatory in Hawaii and the La Palma Observatory in Spain.

The Lenghu Observatory site in China has a clear night percentage of 70%, with a median seeing value of $0\farcs75$, and 75% of the time exhibiting seeing conditions below $1''$ (Deng et al. 2021). Located at the highest point of the Antarctic ice sheet, Dome A (elevation 4096 m) is currently the best astronomical observation site on Earth in terms of seeing, with a median seeing value of only $0\farcs31$. At a height of 14 m, 49% of the time the seeing is better than $0\farcs3$ (Ma et al. 2020), making the observational conditions second only to those in space. The AST3-2 (Antarctic Survey Telescope) is currently the only survey telescope operating at Dome A in Antarctica (see Figure 1).

Reliability refers to the ability of a system to perform a specific function without failure under designated conditions. The reliability of drive control systems has long been regarded as a critical evaluation metric for the sustained operational stability of instrumentation and equipment, and research into system reliability across various industries has never ceased. Key reference indicators for measuring system reliability include Mean Time Between Failure (Lall et al. 2020), Mean Time Between Repair (Jiang et al. 2021), Failure Rate (Qiu et al. 2015), and Redundant Design (Saikai et al. 2022). Pursuing a drive control system with higher reliability is one of the key factors in enhancing the efficiency of astronomical observations conducted with telescopes (Rodeghiero et al. 2018).

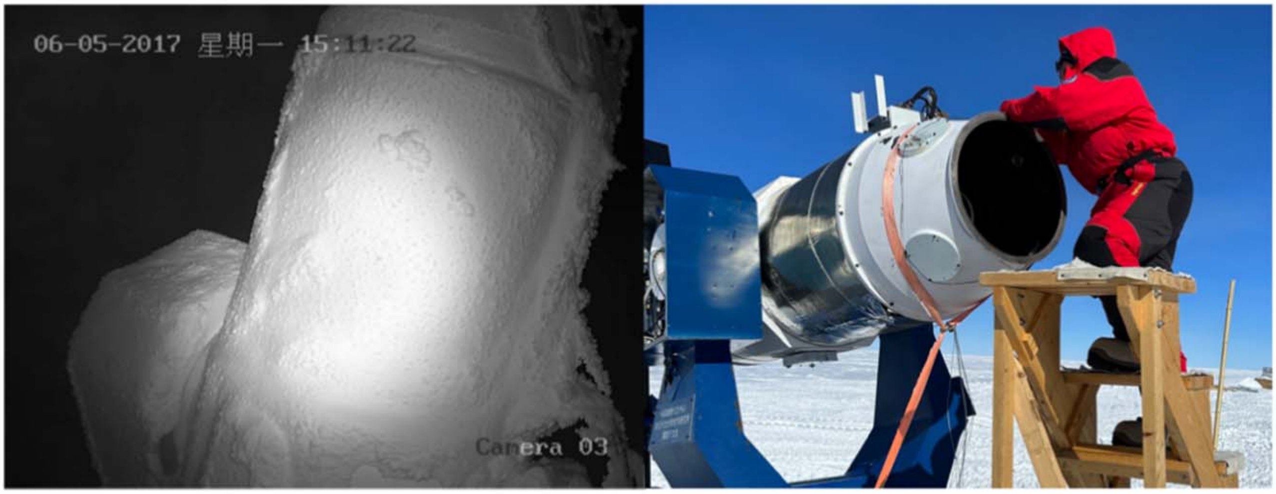


Figure 1. The Antarctic Survey Telescope working in the polar night and the author conducts maintenance of the telescope at Dome A during the polar day.

Quantitative reliability analysis has been widely applied since the 1950s, gradually evolving into a distinct discipline and expanding its applications across various fields, including electronics (Song & Wang 2013), power (Wang et al. 2022), mechanics (Duan et al. 2023), civil engineering (Torres et al. 2020), aerospace (Emmanouil 2020), and astronautics. The United States began its reliability research early, primarily aimed at enhancing the reliability of military electronic equipment (Condra et al. 2015), which subsequently extended to civilian products (Kenwick 2020; Zhai & Ye 2020). Concurrently, countries such as the United Kingdom, Japan, France, and the former Soviet Union also initiated research into reliability theory and its applications. In China, research on reliability started relatively late, initially focused on verification testing for the reliability of electronic components within the aerospace sector. This research gradually became standardized through the issuance of relevant regulations and standards, laying a foundation for theoretical research and practical applications.

The reliable operation of telescopes over extended periods is crucial for astronomical observations, particularly for tracking observations of specific targets, as reliability directly impacts the continuity of data acquisition and analysis (Uunila & Kallunki 2015). Given the lengthy development cycle of telescopes, with structural lifespans potentially extending to several decades and significant costs involved, upgrading and retrofitting existing systems has become an essential pathway for enhancing both reliability and performance, especially in light of advancements in technology and increasing scientific demands. The Keck Telescope and the Large Binocular Telescope have both undergone systematic hardware and software upgrades to improve their performance and reliability, yielding significant results (Brusa et al. 2020). The Telescopio Nazionale Galileo, which has been operational for 20 yr, has maintained its original observational performance and sustained reliability through upgrades to its drive control system (Ghedina et al. 2016). To enhance the pointing and tracking performance of the KPNO Mayall 4 m telescope, as well as to improve the maintainability of the Telescope Control System, upgrades to the telescope's servo system have been implemented in both hardware and software (Sprayberry et al. 2016).

Considering reliability comprehensively from the design phase is a prevailing approach in the development of modern telescopes. The Thirty Meter Telescope (TMT) is currently the second-largest ground-based optical telescope project under construction internationally. It features a dedicated monitoring and control system designed to interact with the telescope's safety systems and respond to errors and alarms, thereby enhancing performance in terms of availability, safety, reliability, and maintainability (Marshall et al. 2006). To assess the operational reliability of the TMT, researchers have developed a reliability assessment model aimed at evaluating the telescope's sensitivity to failures (Rogers et al. 2022). To enhance reliability and reduce maintenance requirements, the Cherenkov Telescope Array has equipped its control system with a specialized safety and health monitoring system (Antolini et al. 2016). Software reliability design plays a critical role in the operational reliability of telescopes; for instance, the Very Large Telescope (VLT) control software must coordinate a vast array of equipment across four 8 m telescopes, necessitating higher standards for software reliability design. Additionally, employing fault-tolerant algorithms to enhance the reliability of telescope observation control systems is also a significant strategy.

Redundant design is regarded as one of the most commonly used and effective strategies for enhancing reliability, and it is

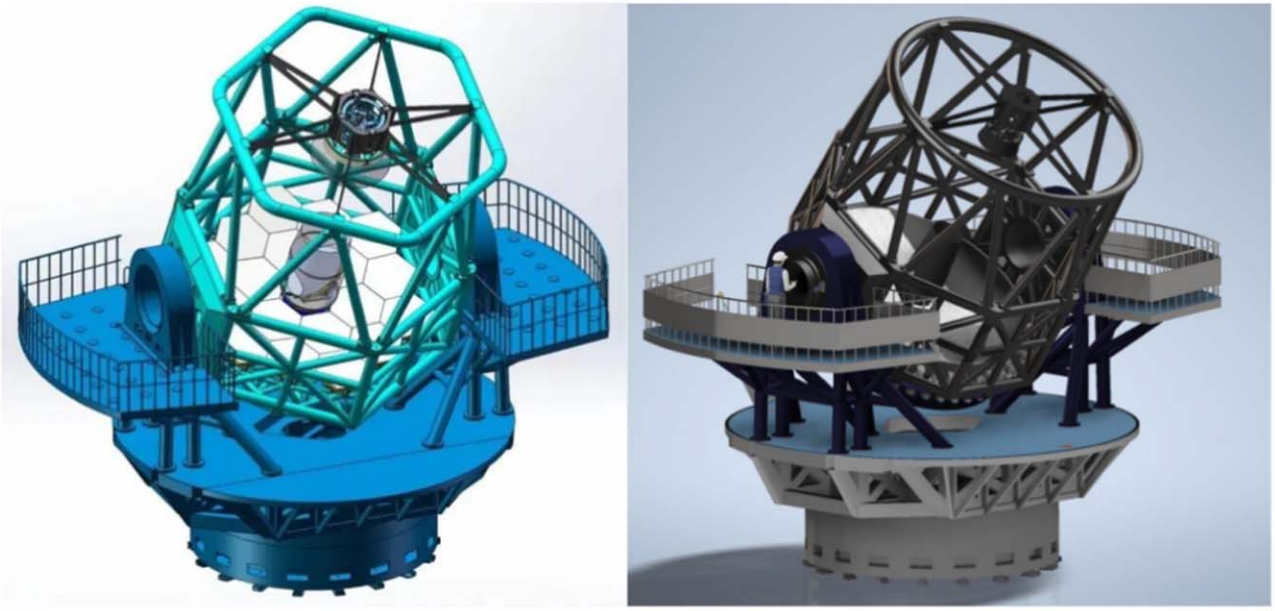


Figure 2. The 4.4 m and 4.2 m telescopes under development in China.

widely applied in the design of telescope drive control systems. The multi-readhead design of the azimuth and altitude axis encoder not only improves accuracy but also serves as a redundancy measure; the abnormal data from one or more readheads does not affect the telescope's positional acquisition. Multi-readhead is a encoder equipped with multiple readheads, and the position is obtained by processing of the data from multi-readhead. The design can reduce some higher harmonics errors (Lu et al. 2019), and improve the position feedback accuracy to a certain extent. At the same time to achieve the purpose of redundancy and backup, a single readhead failure can be eliminated through the software mode of its data, does not affect the telescope position feedback. This design is more common in telescope spindle position feedback, for example, the Azimuth and Cassegrain axes of VISTA telescope use a single full-circular encoder tape with four readheads (Sutherland et al. 2015). Redundant design is particularly prevalent in Antarctic telescopes. For instance, designs such as dual motor drives (Wang et al. 2022), multiple power supply controls, and dual master control systems (Du et al. 2016) are all effective measures for enhancing the operational reliability of telescopes.

China has a number of optical telescopes in the 4–8 m range, as well as the next generation 14.5 m optical-infrared telescope under development (Su et al. 2017). The 4.4 m spectroscopic telescope Jiao Tong University Spectroscopic Telescope (Liu et al. 2024) from Shanghai Jiao Tong University and the 4.2 m ground-based astrometric telescope from the Purple Mountain Observatory of the Chinese Academy of Sciences will fall behind the Cold Lake Observatory (Figure 2). The 6.5 m wide-field survey telescope Multiplexed survey telescope (Zhang et al. 2023), being established by Tsinghua University, and the 6–8 m growth-type general optical telescope Expandable Aperture Segmented Telescope from Peking University have also entered the implementation phase. The China Antarctic Observatory plans to construct a 2.5 m large-aperture optical/infrared telescope, known as the Kunlun Dark Universe Survey Telescope (Zhu et al. 2014), and a 5 m terahertz telescope DATE5 (Yang et al. 2012) at the Kunlun Station located in the Dome A region. This initiative also proposes a long-term development plan that includes the construction of 6–8 m optical/infrared telescopes and a 15 m terahertz telescope as the primary equipment.

The rest of this paper is organized as follows: Section 2 presents the notion of Telescope drive control system and reliability. Section 3 elaborates on strategies for enhancing the reliability of telescope drive control systems from three perspectives. Section 4 describes the integration of theory and application according to the method in Section 3. Section 5 summarized the whole paper and details further research plans.

2. Telescope Drive System and Reliability

The telescope drive control system is a crucial component in the development process of the telescope itself and serves as the key actuator for ensuring the normal tracking and observation of celestial objects. The reliability of the drive control system is directly related to tracking accuracy and the successful execution of sustained observational activities, making it a critical indicator for evaluating the precision tracking and control performance of the telescope.

2.1. Notion of Telescope Drive System

The reliability study of the telescope drive control system involves the operational stability of various components, including the azimuth axis, altitude axis, focusing mechanism, de-rotation mechanism, focal plane mechanism, mirror cover, and dome. The long-term stable operation of the azimuth axis, altitude axis, and de-rotation mechanism ensures high-quality pointing accuracy during the tracking observation process, while the focusing and focal plane mechanisms contribute to maintaining the quality of the astronomical images.

The drive control system is a closed-loop system that includes a host computer, controllers, drivers, actuators, and feedback devices. Each controlled object can be operated independently or in a coordinated manner. The basic principles of telescope drive control are illustrated in Figure 3.

2.2. Notion of Reliability

The first author of this paper has been engaged in the research on the reliability of telescope drive control system since his postgraduate study, and has made various attempts to improve the operational reliability of the telescope from different perspectives and with different strategies. During his Master's program, he primarily conducted qualitative analyses of the system's weak points using Fault Tree Analysis (FTA), which provided direction for system optimization. Additionally, he developed a diagnostic and self-healing expert system for anticipated failures, which is one of the effective methods for improving system operational reliability.

The author's doctoral studies focus on the identification and localization of unanticipated states, establish a three-layer generic process model for such states. He proposed a method for recognizing unanticipated states based on time-domain feature vectors and explored the applications of Support Vector Machines (SVM), One-Class Support Vector Machines, and Principal Component Analysis (PCA) in the identification of unanticipated states. During his postdoctoral research phase, he built upon the foundations laid during his Master's and doctoral studies, with a thorough understanding of the weak points in the telescope drive control system. The authors optimized the tracking control accuracy and reliability, applied these improvements to telescope development projects. The principle of reliability enhancement mechanism for telescope drive system is shown in Figure 4.

Based on author years of research experience and professional background, the methods for enhancing the reliability of telescope drive control systems can be categorized into three main strategies:

1. *Diagnosis, Self-Healing, and Prediction of Anomalous States*. Fault diagnosis and self-healing technologies can significantly enhance diagnostic efficiency, thereby greatly reducing the mean time to repair and indirectly improving system operational reliability. Fault prediction techniques can identify anomalous states at an early stage of failure, preventing more severe downtime and proactively addressing potential issues. This approach also includes the handling of unanticipated states, which constitutes one of the strategies for indirectly enhancing system operational reliability.
2. *Regular Inspection, Maintenance, and Updates*. Conducting regular inspections and maintenance on specific components according to the system's operational cycle is another common strategy for improving operational reliability. For example, during non-observational periods of the telescope, preventive inspections and maintenance can be carried out on components with a higher incidence of anomalies based on operational experience, and timely updates can be made for parts that have reached their expected lifespan.
3. *Optimization During the Design Phase.* As the first two methods primarily address symptoms rather than root causes, they enhance reliability indirectly through improved maintenance efficiency. Most studies indicate that optimizing system design based on the weak points identified during fault diagnosis and regular inspections is the most fundamental approach to enhancing reliability and represents the best means of addressing the root causes of reliability issues. Common optimization design methods include redundancy design, algorithm optimization, and program simplification, which have gradually been applied in the design of telescope drive control systems. The drive control of the Antarctic Survey Telescope adopts the redundant design scheme of dual motors and dual masters to enhance the reliability of operation in extreme environments (Li et al. 2018). Observation strategies optimized based on deep reinforcement learning algorithms can enhance the operational efficiency of telescope arrays (Jia et al. 2023), which is instrumental in conducting time-domain astronomy research. Excessive complexity reduces system stability to a certain extent, and simplified design solutions may yield better results, as is the case with the open sunshield architecture of the space telescope (Feinberg et al. 2012).

3. Reliability Improvement Strategies

3.1. Anticipated Fault Diagnosis and Self-healing

A commonly used solution for addressing existing faults is to establish a Fault Diagnosis and Self-healing Expert System (FDSES) that facilitates the identification, diagnosis, self-healing, and prediction of faults. The Expert System, based on a reasoning engine, enables rapid identification and diagnosis of existing faults. Adaptive adjustments based on parameters

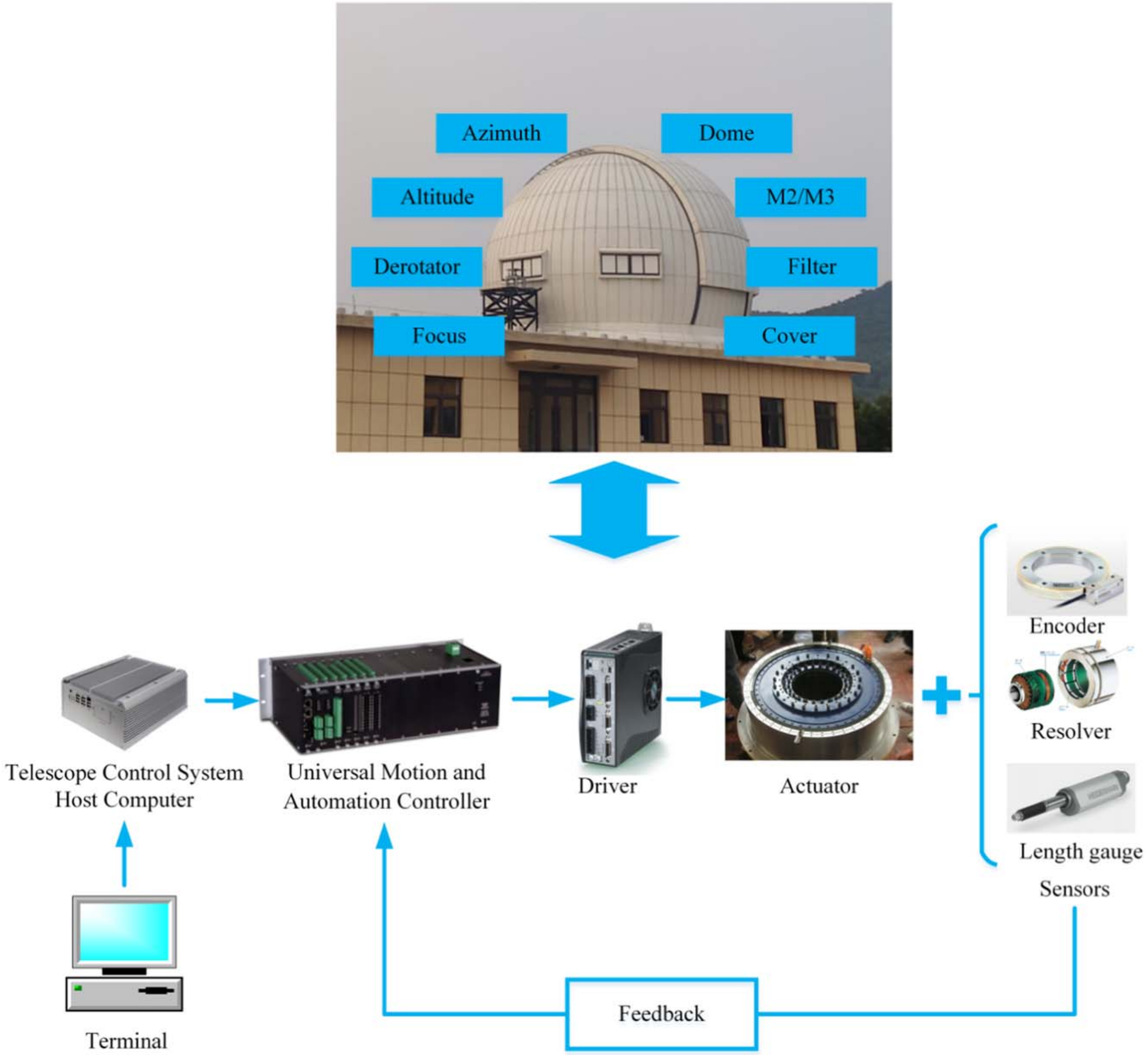


Figure 3. Telescope drive system schematic diagram.

and intelligent switching through redundancy design facilitate self-healing under specific operational conditions, while artificial intelligence algorithms are employed for the prediction of anomalous states. Enhancing diagnostic efficiency, reducing operational maintenance time, and proactively predicting potential faults represent effective strategies for improving the long-term operational reliability of telescope drive systems.

The FDSES for telescope drive systems addresses complex issues such as logical reasoning, linguistic description, and data analysis and processing through computer programming. This enables the system to tackle faults in telescope drive systems with the capabilities and reasoning of experienced experts. The expert system for diagnosis and self-healing should encompass functions for fault identification, localization, self-healing, and prediction, consisting of seven components: the upper-level computer of the diagnosis and self-healing expert system, a monitoring data acquisition and processing center, an integrated database, a knowledge acquisition module based on fault trees, a diagnosis and self-healing knowledge base, a brain-like reasoning engine, and an explanation and diagnostic logging mechanism.

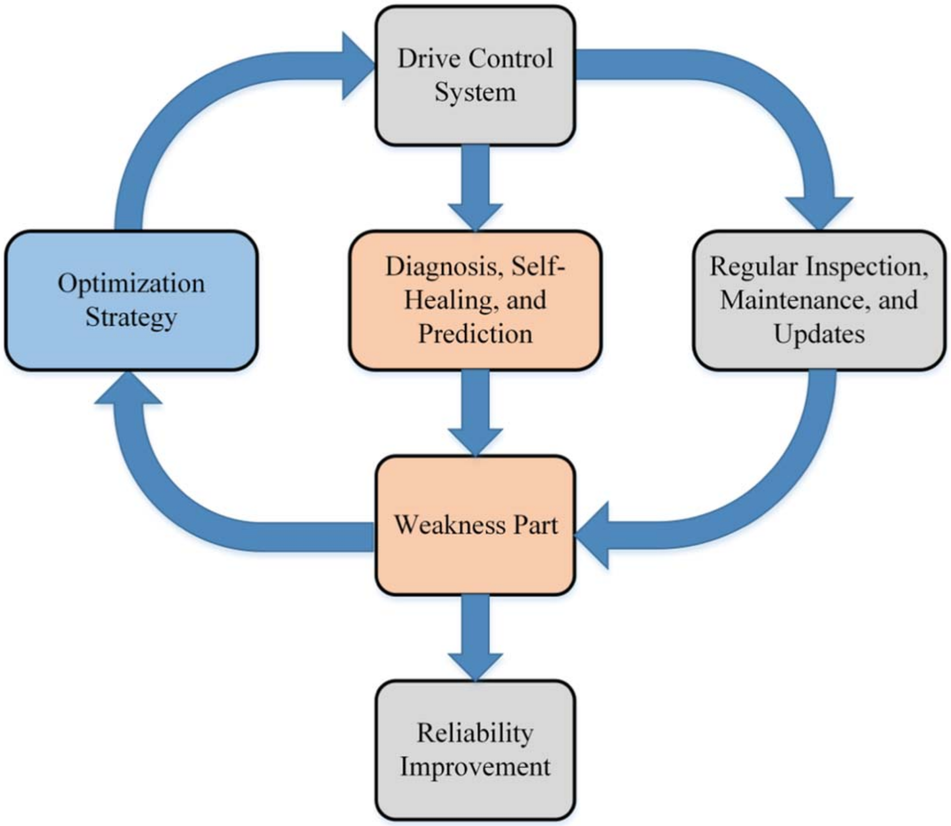


Figure 4. Principle of reliability enhancement mechanism for telescope drive system.

The design principle diagram of the FDSES for the telescope drive system is shown in Figure 5.

3.2. Unanticipated States Recognize

Anticipated faults are those that occurred during testing or previous work, and they usually have a priori information that is already present in the fault mode library. Unanticipated states exist objectively beyond the realm of anticipated states, but due to the lack of corresponding a priori information, neither sufficient monitoring records, acquisition means and characterization, nor the existence with the failure mode library. However, not all unanticipated states are fault states, which contain both unanticipated normal states and unanticipated fault states.

For example, a telescope working at different ambient temperatures, the drive current will behave differently due to changes in the characteristics of the mechanical structure. A telescope working in winter will have a higher drive current than in summer, and a higher current at night than during the day. But the above changes are not a fault and do not affect the normal operation of the telescope, so they are called unanticipated normal state. Moreover, due to the huge size of the VLT, it is difficult to get the pattern of current fluctuations due to temperature changes in advance. Failures that affect the normal operation of the telescope and for which the cause is unknown are called unanticipated failures, such as drive overcurrent protection.

The solution for unanticipated states is based on a three-layer generic process model, which incorporates a temporal feature vector method for unanticipated state identification and an offline detection algorithm based on SVM. The first layer of the three-layer generic process model is the expected fault diagnosis layer, which corresponds to the solutions provided by the expert system for diagnosed and self-healing faults discussed in the previous section. The second layer, the unanticipated normal state isolation layer, and the third layer, the unanticipated fault state identification layer, are specifically designed to address unanticipated states.

The purpose of the unanticipated normal state isolation layer is to assess and isolate states that exceed the anticipated normal thresholds, thereby reducing the false alarm rate. The objective of the unanticipated fault state identification layer is to

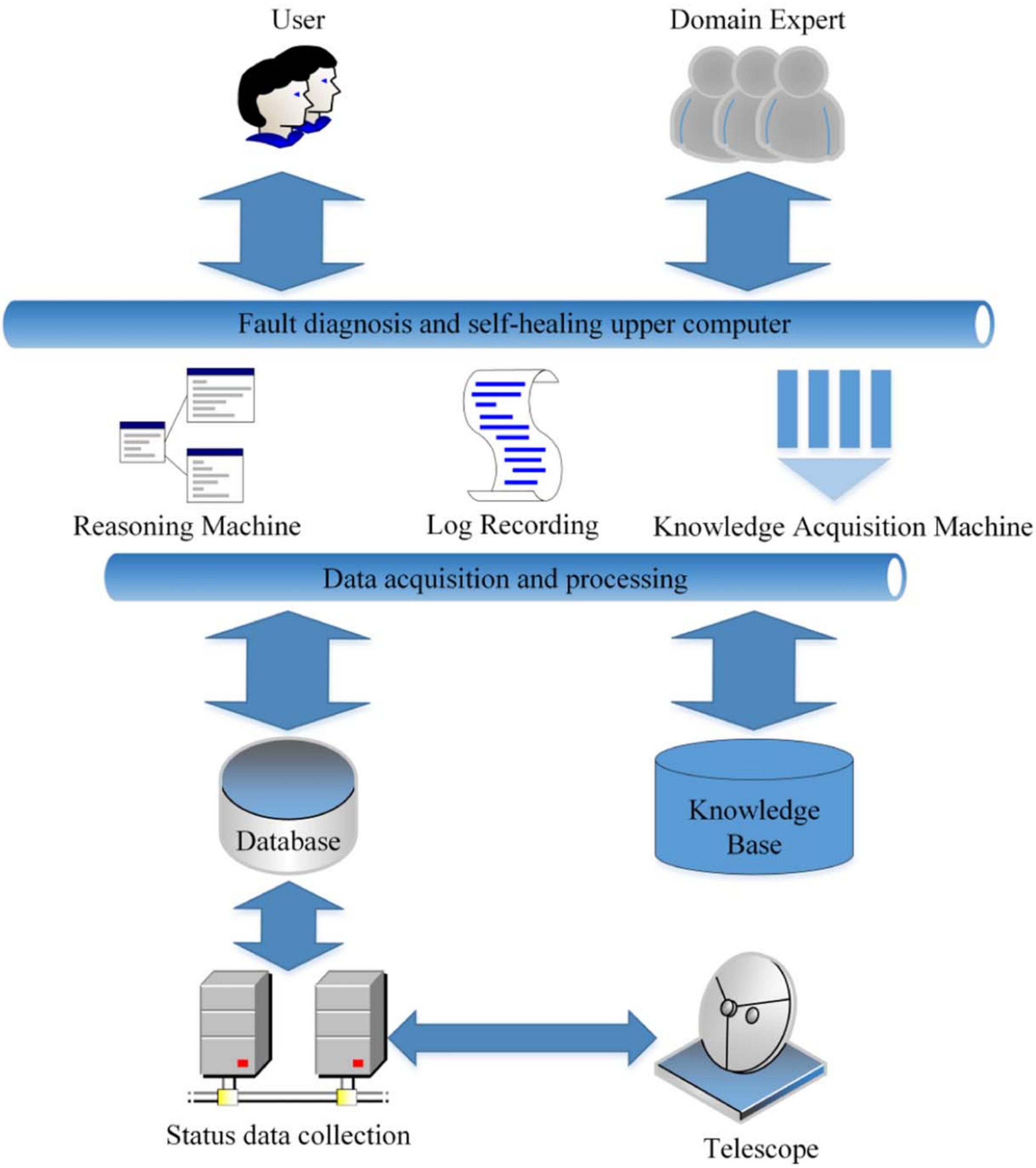


Figure 5. Design principle diagram of Fault Diagnosis and Self-healing Expert Systems for telescopes.

recognize unanticipated fault states, aiming to decrease the miss alarm rate.

The unanticipated normal state isolation layer contains isolation rules based on angular deviation and amplitude deviation, and detailed derivations of the qualitative analysis and quantitative calculation of these rules have been published (Li et al. 2021). If the relevant sample data for a given state satisfies these isolation rules, it indicates that the state is classified as an unanticipated normal state. Additionally, the model will incorporate the data characteristics and descriptions exhibited by this state into the existing anticipated normal pattern library, effectively transforming the unanticipated normal state into an anticipated normal state. This approach prevents redundant operations when the system encounters this

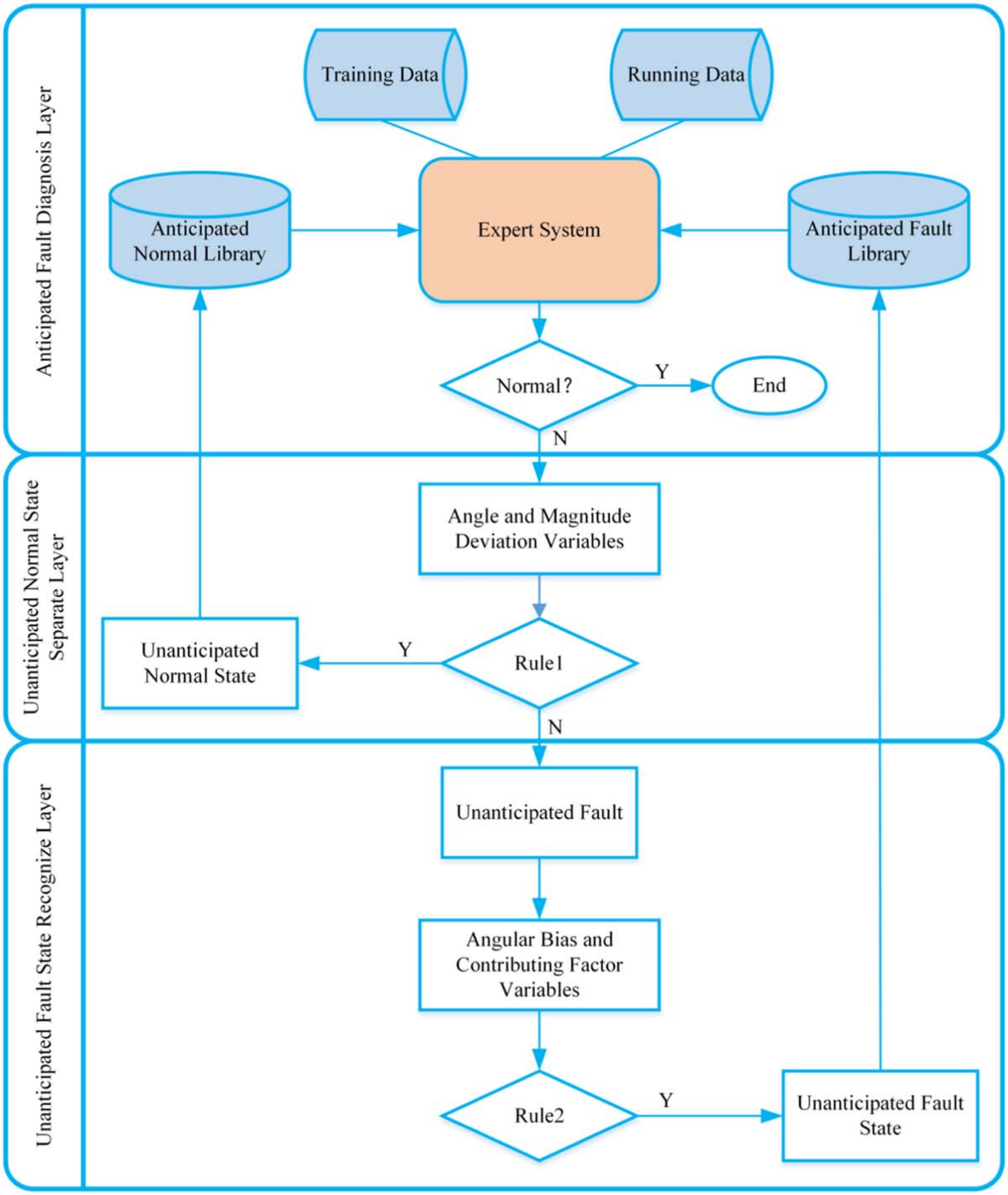


Figure 6. Three-layer generalized process model for unanticipated state identification.

state again, thereby enhancing the efficiency of the model in isolating unanticipated normal states and reducing the overall burden on the system.

The unanticipated fault state identification establishes a method for recognizing unanticipated faults based on the combination of angle deviation and contribution factors. When a fault occurs during system operation that has not been previously documented in the anticipated fault pattern library, it may lead to a failure in the anticipated fault diagnosis system. In such cases, the unanticipated fault identification method is required to assess and recognize the fault. This is achieved by calculating the angle deviation between the fault feature vector

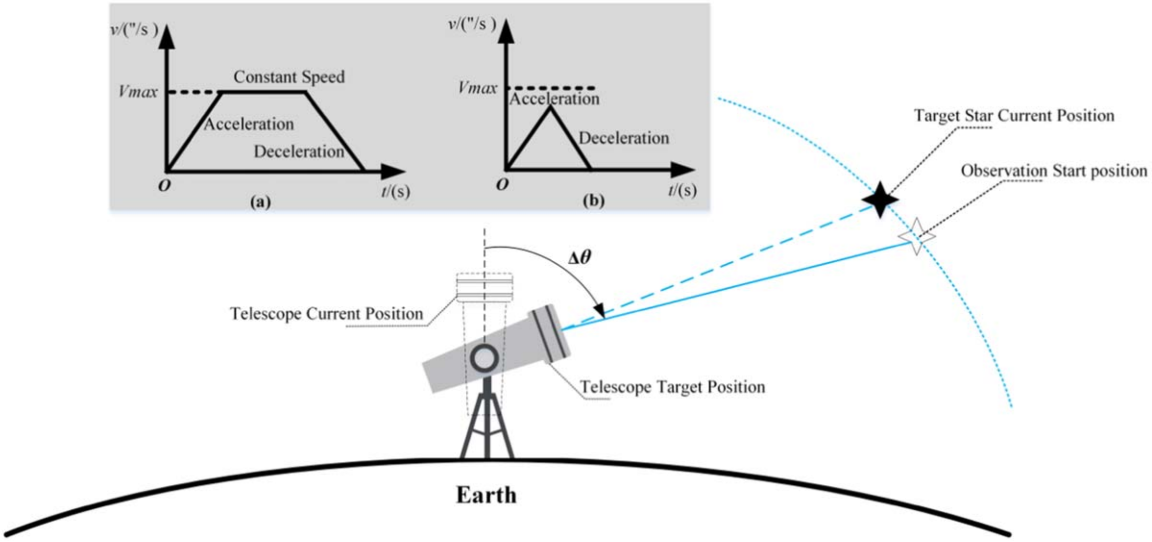


Figure 7. Schematic diagram of the telescope to achieve tracking.

and the anticipated fault feature vector, and determining the maximum contribution factor of the anticipated fault to the unanticipated fault based on this angle deviation, thereby enabling the identification of unanticipated states.

The three-layer general process model structure for unanticipated state identification is shown in Figure 6.

3.3. Optimized Design for Tracking Strategy

The process of transitioning a telescope from a stationary state to tracking a target celestial body is essentially a pursuit problem. First, the telescope's upper computer calculates the position of the target celestial body over a specified time interval following the current time and converts this information into the telescope's azimuth, elevation, and roll angle based on celestial coordinates. Subsequently, the telescope rapidly moves from its current position to the target celestial body's location in a high-speed pointing mode. However, since the target celestial body is also in motion during this pointing process, the telescope must continuously adjust its aim to the target position. To achieve precise pointing, this process requires multiple iterations to ensure that the telescope's aim and the target celestial body coincide perfectly at a specific moment in time. Finally, after pointing at the target celestial body, the telescope enters a low-speed tracking phase.

The motion modes of the telescope during the tracking observation process can be categorized into two types: high-speed pointing and low-speed tracking. The maximum speed and acceleration during the pointing motion are known, while the tracking speed corresponds to the actual motion speed of the target celestial body. The high-speed pointing process is further divided into two scenarios based on the critical distance between the telescope's current position and the target celestial body's position. When the distance exceeds the critical threshold, the pointing speed reaches its maximum, resulting in a motion profile characterized by initial acceleration, followed by constant speed, and then deceleration. Conversely, when the distance is less than the critical threshold, the pointing speed does not achieve its maximum, leading to a motion profile that includes initial acceleration followed by deceleration. A schematic diagram of the telescope tracking observation principle is shown in Figure 7.

The original tracking strategy of the telescope is based on the principle of sending the target position individually. This strategy can lead to delays due to frequent interactions between the host computer and the controller, resulting in the accumulation of tracking errors that necessitate frequent error compensation. The optimized tracking control strategy, which involves packaging and sending the target position under a timestamp synchronization method, significantly reduces the interaction frequency, enhances stability, and ensures normal tracking over a certain period even in the event of a control computer failure. The target position of the telescope for 15 minutes is packed together and sent to the controller, and the length of time is determined by the number of registers available to the controller. This work is to reduce the frequency of interaction between the upper computer and the controller, which in turn reduces the network delay, and even if there is a temporary network communication loss within 15 minutes, it will not affect the tracking of the telescope. The timestamp synchronization strategy periodically calibrates the time between the host computer and the

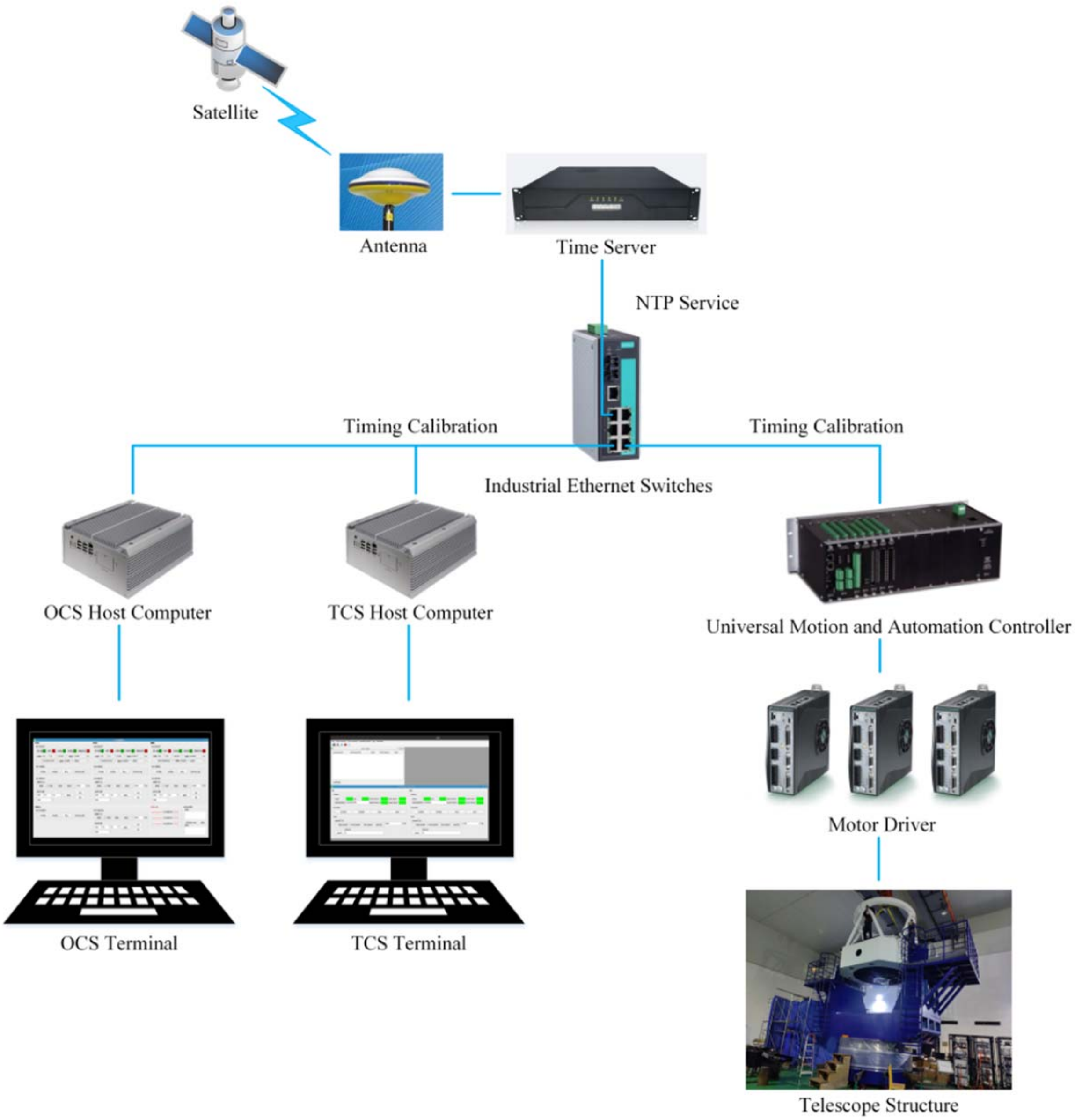


Figure 8. Telescope tracking control strategy based on time synchronization.

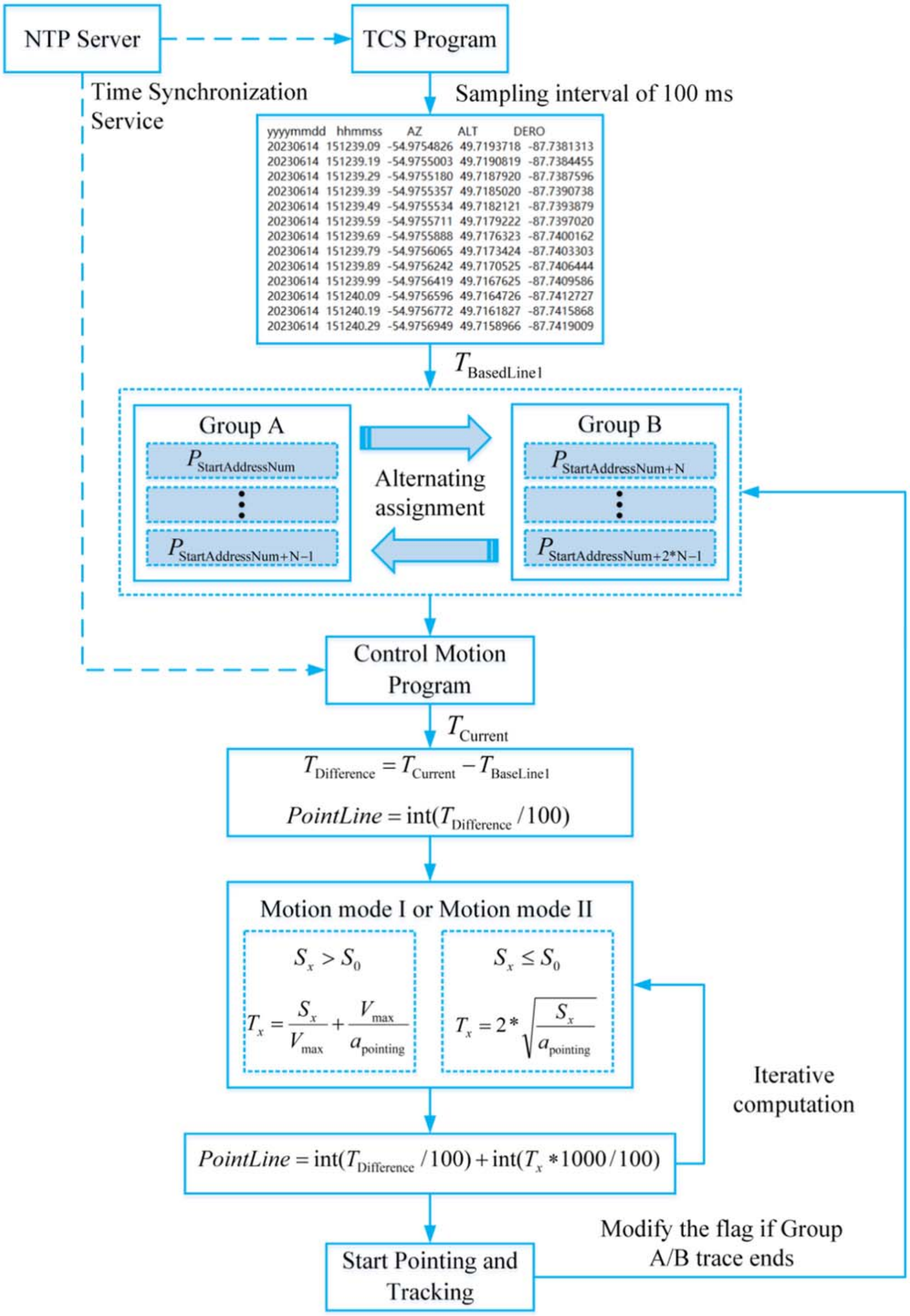
controller, so that when 15 minutes of data are packaged and sent to the controller, the controller can perform location tracking on its own without relying on network communication for 15 minutes.

The time server, host computer, and controller are connected via a fiber optic network through a Gigabit Ethernet switch, forming a Local Area Network. The time server provides time calibration services to the host computer and controller through the Network Time Protocol time service. A schematic diagram of the time synchronization strategy is shown in Figure 8.

The implementation steps of the optimized tracking control strategy for target position packaging and transmission based on timestamp synchronization are illustrated in Figure 9.

Step 1. The master control computer generates a target celestial body position data table at fixed time intervals. This table stores real-time position data of the target celestial body over a specified period, where each data set includes precise timestamps, azimuth position, elevation position, and rotation position. The timestamp of the first row of data is also recorded.

Step 2. The upper computer program packages the position data from the data table and sends it to the controller,



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yyyymmdd  hhmmss       AZ          ALT          DERO
20230614  151239.09  -54.9754826  49.7193718  -87.7381313
20230614  151239.19  -54.9755003  49.7190819  -87.7384455
20230614  151239.29  -54.9755180  49.7187920  -87.7387596
20230614  151239.39  -54.9755357  49.7185020  -87.7390738
20230614  151239.49  -54.9755534  49.7182121  -87.7393879
20230614  151239.59  -54.9755711  49.7179222  -87.7397020
20230614  151239.69  -54.9755888  49.7176323  -87.7400162
20230614  151239.79  -54.9756065  49.7173424  -87.7403303
20230614  151239.89  -54.9756242  49.7170525  -87.7406444
20230614  151239.99  -54.9756419  49.7167625  -87.7409586
20230614  151240.09  -54.9756596  49.7164726  -87.7412727
20230614  151240.19  -54.9756772  49.7161827  -87.7415868
20230614  151240.29  -54.9756949  49.7158966  -87.7419009
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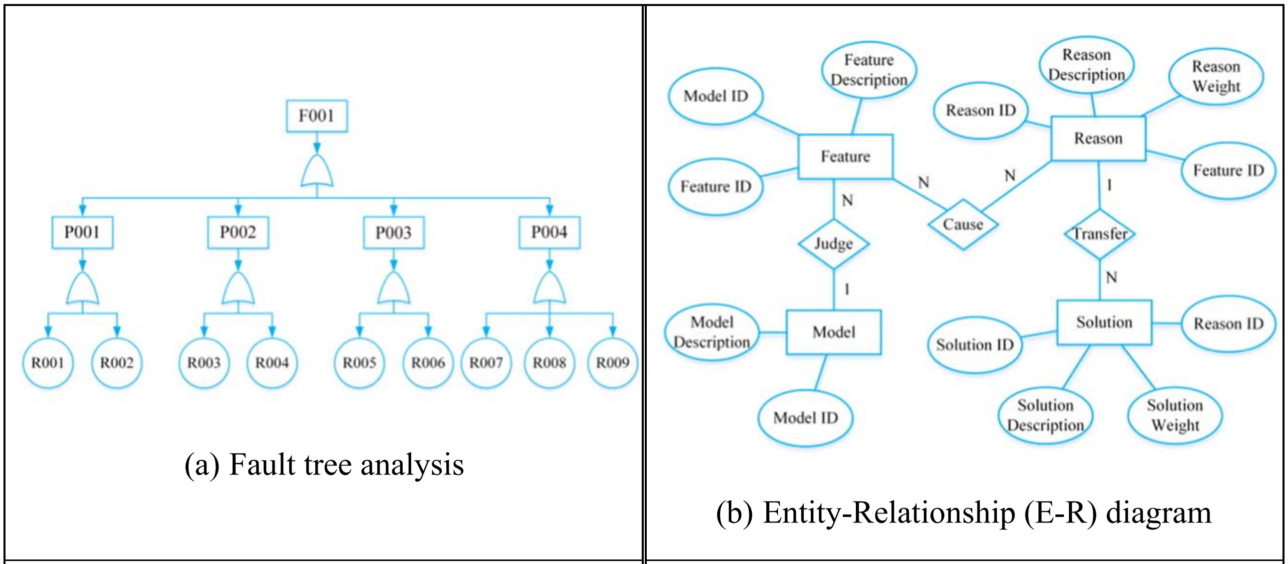
Figure 9. Principle of target location packing and sending strategy under time synchronization.

where it is divided into two groups for storage, with each group containing a fixed number of target position data entries.

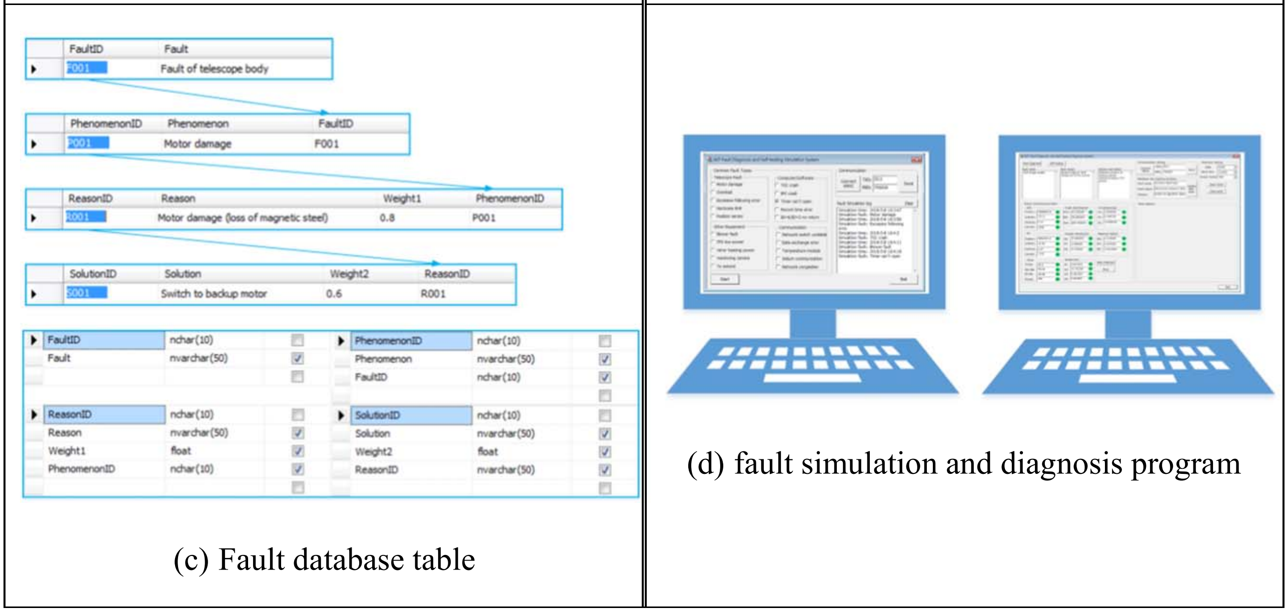
Step 3. The current timestamp is recorded again, and the target position data that the telescope needs to point to is calculated. Based on the current position of the telescope and the designated target position, the telescope begins the pointing operation and adaptively selects the motion mode.

Step 4. The two groups of target position data are executed alternately, enabling continuous tracking of the target position



(a) Fault tree analysis

(b) Entity-Relationship (E-R) diagram



	FaultID	Fault
▸	F001	Fault of telescope body

	PhenomenonID	Phenomenon	FaultID
▸	P001	Motor damage	F001

	ReasonID	Reason	Weight1	PhenomenonID
▸	R001	Motor damage (loss of magnetic steel)	0.8	P001

	SolutionID	Solution	Weight2	ReasonID
▸	S001	Switch to backup motor	0.6	R001

▸	FaultID	nchar(10)	☐
	Fault	nvarchar(50)	☑
			☐

▸	PhenomenonID	nchar(10)	☐
	Phenomenon	nvarchar(50)	☑
	FaultID	nchar(10)	☑
			☐

▸	ReasonID	nchar(10)	☐
	Reason	nvarchar(50)	☑
	Weight1	float	☑
	PhenomenonID	nchar(10)	☑
			☐

▸	SolutionID	nchar(10)	☐
	Solution	nvarchar(50)	☑
	Weight2	float	☑
	ReasonID	nvarchar(50)	☑
			☐

(c) Fault database table

(d) fault simulation and diagnosis program

Figure 10. Implementation of telescope fault diagnosis and self-healing expert system.

by the telescope until all positions in the data table have been processed.

4. Intergration of Theory and Application

4.1. Fault Diagnosis and Self-healing Expert System

FTA is a typical reliability analysis method that can be used to identify weak points in a system, guide system optimization design, and is also applied in the diagnosis of telescope failures and the acquisition of knowledge for self-healing expert systems. A fault tree is constructed based on an empirical database of system failures, representing the intrinsic relationships between system-level failure phenomena (top events) and their most fundamental causes (bottom events) in a hierarchical tree structure. Events at different levels are interconnected through logical relationships such as "AND," "OR," "NOT," and "XOR," with these relationships represented using logical symbols. The fault diagnosis method based on component logical structure also utilizes the system model to deduce the set of components that cause failures by comparing the actual behavior of the system with its expected behavior through logical inference.

The design of the knowledge base for the telescope FDSES adopts an associative database approach. This method

Figure 11. Semi-physical simulation platform for diagnostic and self-healing expert system.

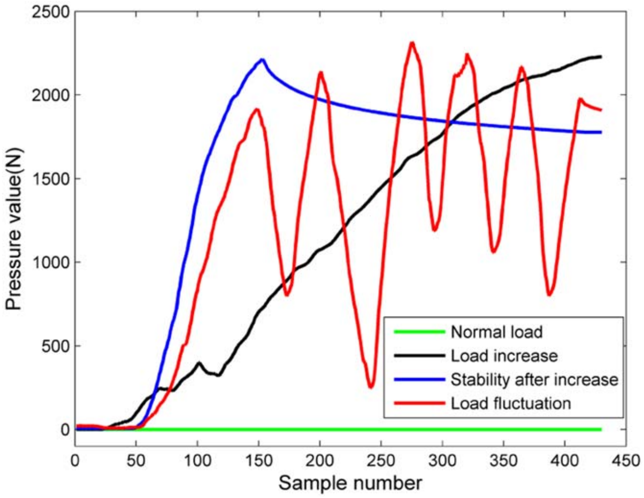


Figure 12. Pressure values under different unanticipated load conditions. Reproduced from (Li et al. 2022). © 2022. The Astronomical Society of the Pacific. All rights reserved.

leverages the inherent advantages of databases to enhance inference efficiency while facilitating the expansion and maintenance of the expert system's knowledge base. The most critical aspect of the database design phase is how to transform the real-world relationships among fault modes, fault phenomena, fault causes, and solutions within the telescope fault knowledge into a relational schema, specifically by establishing an Entity–Relationship (E–R) diagram. In this study, the physical schema design of the telescope fault database primarily focuses on the relationships among the four entities: fault modes, fault phenomena, fault causes, and solutions.

In designing a database-based knowledge base, existing expert knowledge is stored in four tables: Fault, Phenomenon, Reason, and Solution. The Fault table is primarily used to store fault modes and consists of two fields: FaultID and Fault, which are used to store the fault number and the name of the fault mode, respectively. The Phenomenon table is designed to store fault phenomena and contains three fields: PhenomenonID, Phenomenon, and FaultID, which are used to store the fault phenomenon number, the description of the fault phenomenon, and the corresponding fault number. The Reason table is intended for storing fault causes and includes four fields: ReasonID, Reason, Weight, and PhenomenonID, which are used to store the fault cause number, the description of the fault cause, the weight attributed to that fault cause, and the associated fault phenomenon number. Finally, the Solution table is dedicated to storing solutions and contains four fields: SolutionID, Solution, Weight, and ReasonID, which are used to store the solution number, the description of the solution, the weight associated with that solution, and the corresponding fault cause number.

The field FaultID serves as an index for storing fault modes, which facilitates the inference from fault modes to fault phenomena. Similarly, the PhenomenonID index enables the inference from fault phenomena to fault causes, while the ReasonID index allows for the inference from fault causes to fault solutions.

The software for the telescope FDSES includes a fault simulation interface as well as a diagnosis and self-healing interface. The simulation upper computer sends fault simulation commands, while the diagnosis and self-healing upper computer executes diagnostic functions. The system automatically determines the fault location of the telescope based on relevant parameters and subsequently searches the expert system knowledge base for corresponding fault causes and solutions. If the system is unable to diagnose the simulated fault type, the human-machine interface allows for timely updates to the expert system knowledge base, thereby enhancing its extensibility. Additionally, the upper computer

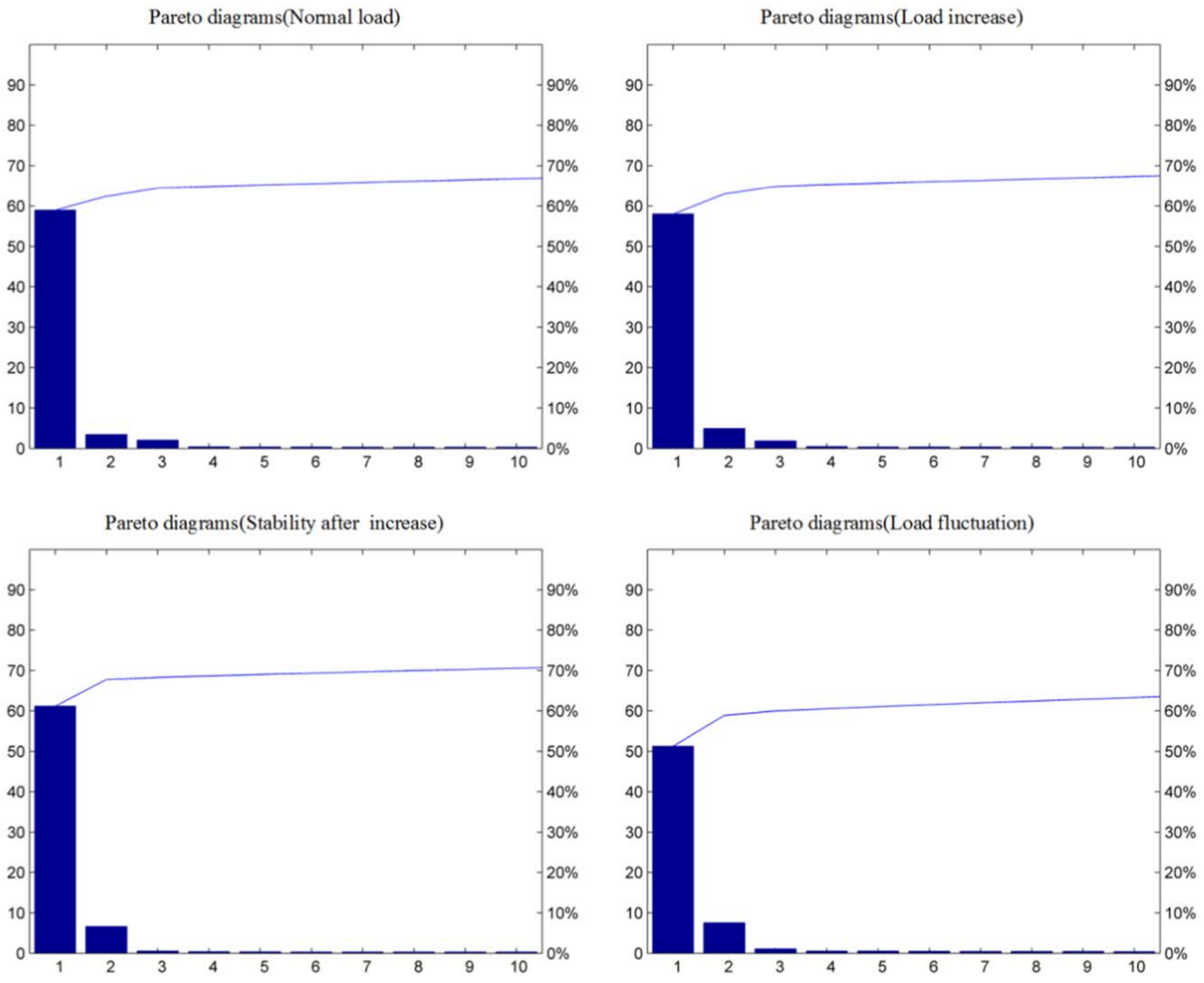


Figure 13. The pareto plot distribution obtained by the PCA. Reproduced from (Li et al. 2022). © 2022. The Astronomical Society of the Pacific. All rights reserved.

software features a telescope status monitoring and alarm module, which primarily conducts real-time monitoring of the telescope's operational status by collecting parameters from controllers and external sensors.

Figure 10 shows the construction process of the telescope FDSES, in which Figure (a) is the use of FTA to obtain the knowledge base, Figure (b) is the use of the knowledge base to construct the ER diagram, Figure (c) is in the implementation of the database reasoning mechanism, and Figure (d) is the software interface of the expert system for fault simulation and diagnosis.

The FDSES operates on the telescope semi-physical simulation platform to validate its performance. It consists of a fault simulation chassis and a diagnosis and self-healing chassis. The fault diagnosis and self-healing semi-physical simulation platform is illustrated in Figure 11.

4.2. A General Process Model for Unanticipated State Recognition

The data mining approach based on PCA plays a crucial role in identifying unanticipated states associated with abnormal fluctuations in the telescope's load (Li et al. 2022). This method effectively uncovers hidden information within the data, thereby facilitating the identification of unanticipated states. By combining a latent variable extraction strategy that employs stable kernel representations as detection statistics with an unanticipated detection strategy utilizing PCA, the feasibility of this method has been validated through

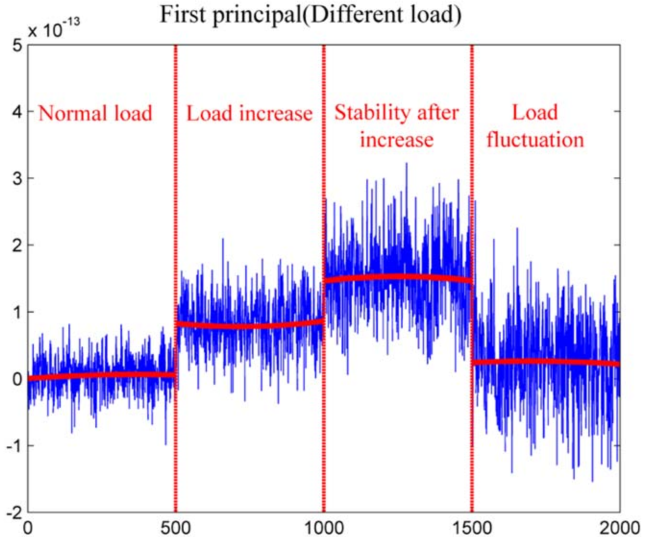


Figure 14. Unanticipated state identification results based on data mining. Reproduced from (Li et al. 2022). © 2022. The Astronomical Society of the Pacific. All rights reserved.

Table 1
Information of the Fixed Star HIP 15863

Mirfak—HIP 15863—SAO 38787—HD 20902—HR 1017	
Type:	Double star
Magnitude:	1.75
Absolute Magnitude:	−4.12
Ascension/Declination (J2000.0):	$3^{\mathrm{h}}\ 24^{\mathrm{m}}\ 19^{\mathrm{s}}.37\ /49^\circ\ 51'\ 40''.25$
Ascension/Declination (Current):	$3^{\mathrm{h}}\ 26^{\mathrm{m}}\ 06^{\mathrm{s}}.23\ /49^\circ\ 56'\ 57''.9$

experimental platforms that assess unanticipated variations in the telescope's drive system load.

The performance of unanticipated load anomalies under different forms as shown in Figure 12, where the horizontal coordinate represents the number of samples and the vertical coordinate represents the value of load pressure. The pareto plot distribution (as shown in Figure 13) obtained by the PCA shows that the first principal element contains the most important data features and can be used to represent the characteristic performance of the load unanticipated state. Load anomaly unanticipated state identification results based on data mining is shown in Figure 14.

4.3. Tracking Strategy Optimization

This study employs the 2.5 m telescope to track the star HIP 15863, in order to validate the performance of the tracking strategy for transmitting target positions in packets under time synchronization methods. The 2.5 m telescope is illustrated in Figure 15.

The control system of the telescope primarily consists of a host computer, a controller, a driver, a motor, and a position feedback encoder. The resolution of the encoder is directly linked to the tracking accuracy of the telescope. The 2.5 m telescope utilized in this research platform is equipped with a 29 bit absolute encoder, achieving a resolution of up to $0''.0024$. In contrast, the design specification for telescope tracking accuracy is set at a RMS value of $\leqslant 0''.3$ without the use of a guiding closed loop, which significantly exceeds the established requirements.

The telescope tracked the target HIP 31216 over a duration of 30 minutes to evaluate the dynamic performance of the telescope during prolonged uniform tracking. The position of the star HIP 31216 in the J2000 coordinate system is given as R.A.: $2^{\mathrm{h}}\ 24^{\mathrm{m}}\ 19^{\mathrm{s}}.37$, decl.: $49^\circ\ 51'\ 40''.25$. The detailed information of the star HIP 31216 is shown in Table 1 and its trajectory in one hour period is shown in Figure 16.

During the 30 minutes tracking period, the aim was to assess the dynamic performance of the telescope while tracking a real target. The tracking errors for the azimuth and elevation axes were collected separately. The telescope followed the HIP 31216 for up to 30 minutes, and the following errors in azimuth and altitude are shown in Figure 17 (RMS: $0''.0073$) and Figure 18 (RMS: $0''.0096$). The overall tracking error of the telescope can be calculated by applying the coordinate transformation formula in conjunction with the errors from both the azimuth and elevation axes. Ultimately, the RMS tracking errors of the telescope mount were determined to be $0''.0108$ (as shown in Figure 19), demonstrating excellent tracking performance. The RMS tracking error is based on the encoder data only, which means that the results are only for the analysis of the telescope drive control system itself, and does not include any pointing model bias, so the RMS error is extremely low. However, the high precision tracking error shown in the analysis results indicates that the telescope has a good performance drive control system, which also validates the tracking control strategy proposed in this paper for the target position packaged sending strategy under the time synchronization method.

The 2.5 m telescope, installed at the astronomical observation base, effectively tracks and captures images of various celestial bodies, such as Polaris, Antares, Vega, and Saturn, exhibiting superior image quality (as shown in Figure 20). This clearly indicates the excellent tracking control performance of the telescope.

5. Discussion and Conclusions

Based on the aforementioned research, this paper aims to enhance the operational reliability of the telescope drive control system through three approaches: solutions for anticipated

Figure 15. The 2.5 m telescope.

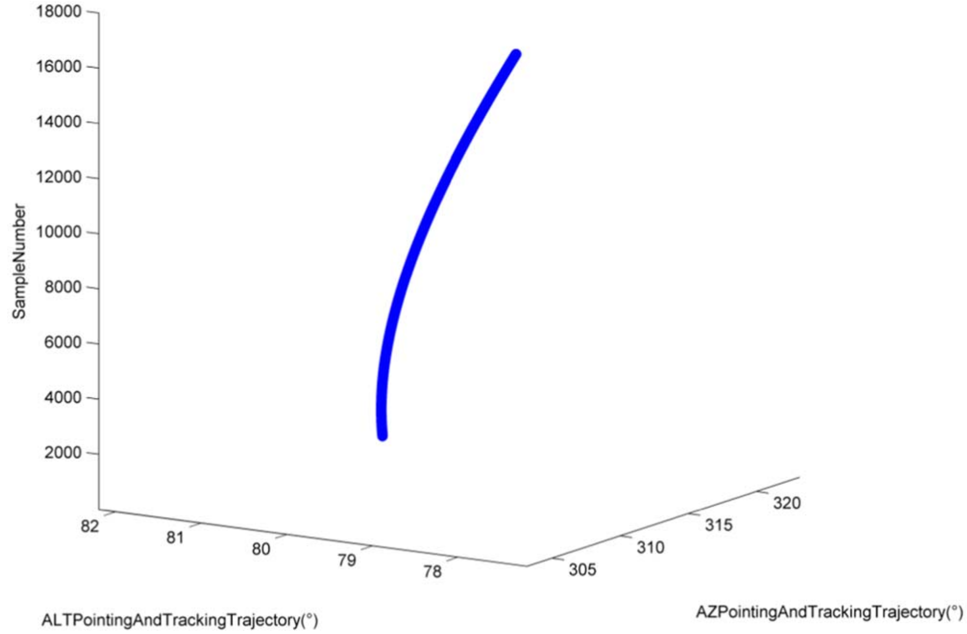


Figure 16. The orbital position of the star HIP 15863.

failures, strategies for handling unexpected conditions, and proactive optimization design. Various degrees of practical outcomes have been achieved. This study holds significant implications for effectively improving the operational reliability of telescopes, optimizing control strategies, and enhancing maintenance efficiency. Furthermore, the findings may provide technical support for the development of China's 14.5 m telescope and contribute to the advancement of astronomy in China.

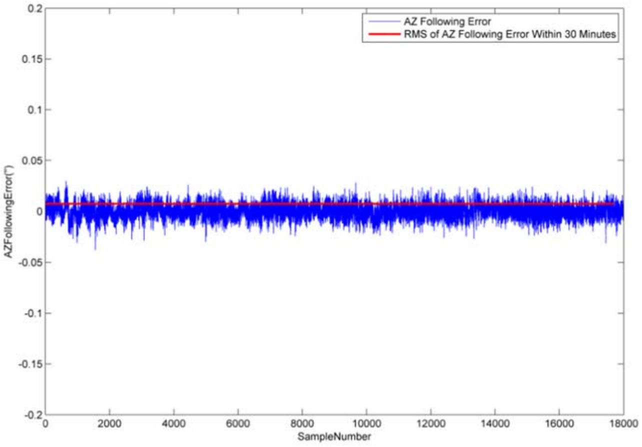


Figure 17. Following error within 30 minutes of AZ.

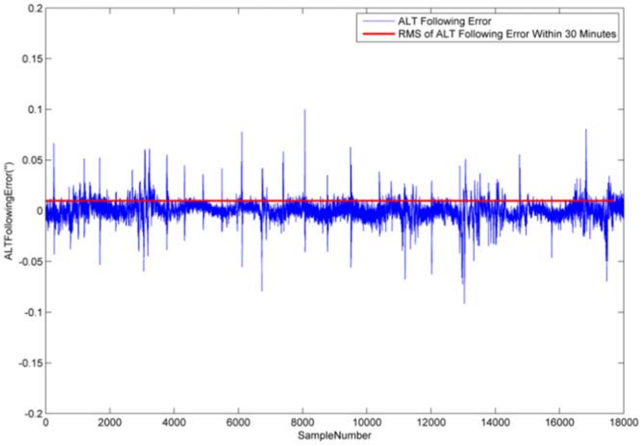


Figure 18. Following error within 30 minutes of ALT.

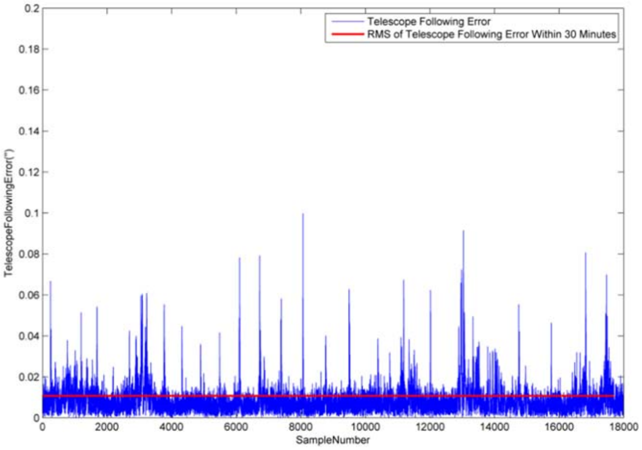


Figure 19. Telescope following error within 30 minutes.

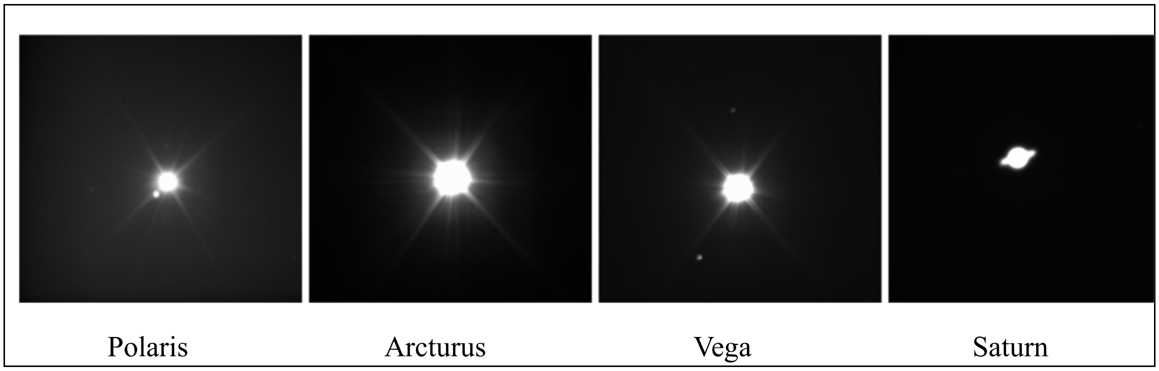


Figure 20. 2.5 m telescope tracking observations.

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