Postprint of the Fault Diagnosis Expert System for the Mini-GWAC Control System

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Abstract

The Ground-based Wide-Angle Camera Array (GWAC) is the ground-based observation facility for the China-France Space-based multi-band Variable Object Monitor (SVOM) astronomical satellite, with Mini-GWAC serving as its pre-research and supplementary project. This paper addresses the Mini-GWAC telescope array, presenting a detailed account of the research and design process for the fault diagnosis system from the perspectives of fault diagnosis methodology, technical design schemes, and fault diagnosis research platforms. Based on the Mini-GWAC telescope platform, this system employs a combined approach of expert system theory and fault tree analysis to conduct research on the fault diagnosis expert system. The research findings are of great significance for improving telescope reliability, reducing maintenance costs, and enhancing observation efficiency, while simultaneously accumulating technical expertise for future application to other telescopes.

Full Text

Fault Diagnosis Expert System for Mini-GWAC Control System

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Abstract

GWAC (Ground-based Wide Angle Cameras) is the ground-based observation instrument of the Sino-French cooperation SVOM astronomical satellite. Mini-GWAC serves as the pre-research project and supplement of GWAC. This paper describes in detail the research and design process of the fault diagnosis system from the aspects of fault diagnosis methods, technical design plans, and fault diagnosis research platforms. Based on the Mini-GWAC telescope platform, we combine expert system theory with fault tree analysis to develop the fault diagnosis expert system. The research results demonstrate that the system can significantly improve telescope reliability, reduce maintenance costs, and enhance observation efficiency, while accumulating technical experience for application to other telescopes.

Keywords: Fault diagnosis; Fault tree; Expert system; Distributed design

1. Introduction

The Ground-based Wide Angle Cameras (GWAC) is the ground-based observation equipment for the Space-based multi-band astronomical Variable Objects Monitor (SVOM), a Sino-French cooperative astronomical satellite. SVOM' s scientific objectives include discovering and observing gamma-ray bursts (GRBs) and studying their radiation characteristics and explosion mechanisms, as well as using GRBs to investigate the early universe and dark energy. GWAC was specifically designed to detect the optical transient radiation of GRBs and other violently variable celestial objects. Comprising multiple wide-angle cameras, GWAC holds a leading international position among similar large-field optical sky survey projects. Its unprecedented capabilities provide Chinese astronomical research groups with opportunities to study numerous particularly interesting frontier and traditional astronomical topics beyond GRBs.

Mini-GWAC, the pre-research system for GWAC, has been installed and commissioned at the Xinglong Observatory of the National Astronomical Observatories. The system consists of multiple telescopes and CCD cameras. Since the observation targets are randomly occurring transient astronomical phenomena and the telescopes operate in a passive observation mode, equipment failures may cause the loss of valuable discovery opportunities. Therefore, understanding and mastering the real-time system status, providing early warnings before faults occur, rapidly locating fault sources and eliminating faults after they occur, and improving system maintainability are urgent problems that need to be solved for such array telescopes. Traditional telescope fault diagnosis methods based on online expert processing are inadequate for these large, multi-tasking systems with numerous devices, making it imperative to build an intelligent fault diagnosis system to minimize scientific losses.

Fault diagnosis involves judging system operating status and abnormal conditions to provide a basis for system recovery. It plays an irreplaceable role in improving equipment intelligence, maintainability, and ensuring safe and reliable operation, yielding significant economic and social benefits. Telescope control system fault diagnosis technology in astronomy started relatively late worldwide. The United States and Australia initiated telescope control system fault diagnosis technology research in 1990 and 1994, respectively. After the launch of the Hubble Space Telescope in 1990, subsequent applications revealed high material and time costs for detecting and eliminating telescope control system faults. To reduce technical maintenance issues for remote telescopes and provide technical support for Antarctic telescope repair and lunar settlement plans, NASA Ames Research Center collaborated with companies to develop the AutoScope system, first applying the research results to the Hubble Space Telescope. The Australia Telescope established an intelligent fault diagnosis system that could receive and store telescope data, analyze it, and map it to known fault patterns to achieve fault diagnosis.

In China, researchers have achieved some results in telescope fault diagnosis studies. Experts have proposed applying modern signal processing spectral analysis to astronomical telescope fault analysis. Spectrum analysis of friction drive experimental device vibration signals has demonstrated that spectral analysis can effectively extract frequency characteristics of vibration signals and identify fault sources. For the Five-hundred-meter Aperture Spherical Radio Telescope (FAST), fault diagnosis methods based on cable stress monitoring and displacement node coordinate monitoring have been developed, which can effectively diagnose the active reflector structure with high precision to guide post-fault structural maintenance. Although fault diagnosis technology applications in Chinese telescopes are developing, systematic application cases remain rare. This project' s research results will effectively improve Mini-GWAC telescope reliability, reduce maintenance costs, enhance observation efficiency, and provide technical accumulation for applying such systems to other telescopes.

2. Fault Diagnosis Method Selection

Fault diagnosis methods have developed rapidly based on sensor technology, modern testing technology, computer technology, and artificial intelligence, finding widespread application across various fields. Traditional classification generally divides fault diagnosis methods into three categories: mathematical model-based methods, knowledge-based methods, and signal processing-based methods. A more systematic classification divides them into qualitative analysis and quantitative analysis. Qualitative analysis methods offer simple modeling, easy-to-understand results, and wide application ranges, but their implementation becomes complex for sophisticated systems. Quantitative analysis methods utilize deep understanding of system internals to provide more precise and efficient diagnosis results, but they often rely on accurate mathematical models of the diagnosed object and require large amounts of sample data, with diagnostic accuracy heavily dependent on sample completeness.

Fault Tree Analysis (FTA), developed by Bell Telephone Laboratories in 1962, is an important method for analyzing equipment reliability and safety and represents one of the primary analytical techniques in fault diagnosis. A fault tree is a tree data structure based on Boolean algebra that uses event symbols, logic gate symbols, and transfer symbols to describe causal relationships among various events in a system. The tree root represents the system-level fault (top event), nodes represent intermediate fault events, and leaf nodes represent fault points or ultimate fault causes (basic events). The fault tree construction process starts from the top event based on understanding the system, analyzes fault causes level by level according to the internal logical relationships of events, and extends to the final causes (basic events). Qualitative analysis involves traversing all possible basic events that could lead to the top event. Quantitative analysis has two main aspects: calculating the top event probability from basic event probabilities, and conducting importance and sensitivity analysis of basic events to establish fault diagnosis and maintenance priorities and improve reliability of relatively low-reliability fault points.

Astronomical telescopes are complex systems integrating computer technology, automatic control technology, and sensor technology. Obtaining precise fault diagnosis mathematical models for such complex control systems is extremely difficult. Therefore, the basic method for telescope fault diagnosis adopts knowledge-based rule reasoning combined with fault tree data structure methods. This approach leverages professional astronomical telescope knowledge and experiential knowledge from astronomers, technical support personnel, and observation assistants to establish a fault diagnosis knowledge base, forms reasonable telescope fault reasoning strategies through fault trees, and completes the fault diagnosis process based on status monitoring and processing.

3. Technical Design Scheme

For the Mini-GWAC telescope array, the control system can be divided into several subsystems: telescope equatorial control system, auto-focus control system, CCD control system, and dome control system. These subsystems are integrated through physical and logical methods. Based on modular design principles, each subsystem is studied and designed independently while forming interconnections, creating a complete telescope control system information monitoring network and thus a highly reliable telescope status information monitoring system. Each node in the monitoring network has a simple monitoring method, and through reasonable fault reasoning strategies, the fault diagnosis process is ultimately completed.

The telescope control system fault diagnosis expert system mainly includes the telescope knowledge base, telescope database, inference engine, and human-machine interface. The overall structure of the expert system is shown in [Figure 2: see original paper].

The telescope knowledge base is a structured knowledge cluster required for establishing the fault diagnosis system, including basic knowledge, professional knowledge, and experiential knowledge (general knowledge in the fault diagnosis field), as well as heuristic knowledge (fault boundary conditions and possible fault causes). The database serves as the information and data source for the inference engine, storing real-time records of telescope status. The inference engine is the organization and control mechanism in the fault diagnosis system, using recorded facts and relevant knowledge from the knowledge base to conduct reasoning according to certain strategies to achieve the desired goals. The inference engine contains problem-solving strategies and reasoning methods, receiving information transmitted from the database, processing it with relevant knowledge from the knowledge base, and sending the results to the human-machine interface.

The human-machine interface is the external software interface of the fault diagnosis system and an important medium for users to exchange information with the control system. Since effective knowledge organization is necessary for flexible application of the telescope fault diagnosis system, and considering that Mini-GWAC contains multiple subsystems, the knowledge base adopts a modular design approach. Taking one telescope as an example, the knowledge base includes equatorial knowledge base, control knowledge base, auto-focus knowledge base, and dome control knowledge base. Each sub-knowledge base is interrelated yet relatively independent. This distributed organization facilitates data collection and forms the knowledge base resources required by the overall Mini-GWAC system.

4. Fault Diagnosis System Reasoning Strategy Design

Telescope fault reasoning is completed by the inference engine in the expert system structure. The fault diagnosis system reasoning strategy is shown in [Figure 3: see original paper].

The fault diagnosis strategy is the organization and control mechanism of the telescope fault diagnosis expert system. It uses various state monitoring data collected by telescope sensors at all levels and relevant knowledge sets from the knowledge base to conduct reasoning according to certain strategies. The diagnosis strategy includes fault reasoning methods and fault elimination measures, as well as structural optimization and design of the strategy itself. Since the telescope expert system knowledge base contains both deterministic and non-deterministic knowledge, the Mini-GWAC telescope fault reasoning strategy can adopt a combination of state chain reasoning and fuzzy reasoning methods for such a large complex system.

5. Fault Diagnosis System Research Platform

The research and experimental work on the astronomical telescope control system fault diagnosis expert system is conducted using the Mini-GWAC telescope array deployed by the Lunar-based Optical Telescope Group of the Space Science Department at the National Astronomical Observatories, located at the Xinglong Observatory.

5.1 System Structure Design The Mini-GWAC telescope array employs a distributed architecture with separate control and centralized management. For the multi-telescope array, the fault tree design also follows a distributed philosophy. The telescope system can be divided into equatorial control system, auto-focus system, CCD system, and dome control system. The data or information that each subsystem needs to monitor is shown in .

5.2 Fault Tree Design After distributed modular design of the telescope system, the fault diagnosis process for each subsystem has distinct phases: system power-on self-test, process monitoring diagnosis, and pre-shutdown self-test. Taking the equatorial system as an example, its fault tree design is shown in [Figure 4: see original paper].

According to the fault diagnosis phases, the specific process during system power-on self-test is as follows: The initial state of the control system represents the status before operation after system startup. The fault diagnosis expert system primarily detects the initial state of the control system, makes judgments on abnormal conditions, and automatically provides diagnosis results. Through system comparison and reasoning logic, relevant status information is obtained from intelligent power modules to ensure the control system enters operation in good condition. The expert system then enters real-time online process monitoring.

The main objects of process monitoring are the telescope' s operational status, limit status, and other state and process variables during operation. Process monitoring aims to accurately describe process fault behaviors with precision and real-time capability. If the telescope fails to complete reset, the cause needs to be located and observation assistants must be ensured to leave the dome. The system monitors the legitimacy of sensor and controller status information.

Pre-shutdown self-test requires confirming equipment status to ensure safety after shutdown. When evaluating system safety and reliability, effective measures to reduce and prevent faults must be studied and formulated. When qualitative and quantitative analysis of the main steps reveals that the root node fault probability exceeds the predetermined target, maintenance decisions must be made to determine the most effective maintenance approach for fault handling.

The fault tree has expandable characteristics. As the knowledge base improves and reasoning strategies optimize, the fault tree can continue to grow to better complete status monitoring and fault diagnosis, providing a basis for equipment maintenance and improvement.

5.3 Engineering Design Methods The fault diagnosis expert system generally adopts a distributed architecture, with the host computer as the telescope control computer and the slave computers as various subsystem controllers. Regarding system status acquisition and processing, data is primarily obtained through relevant hardware and from the central database. Telescope status information acquisition and processing includes telescope rotation speed and other digital and analog signals.

The hardware system design mainly includes sensor selection and installation, as well as configuration of data servers and front-end acquisition controllers, plus development of interface protocols. The software system will use LabVIEW as the expert system software development platform. LabVIEW is widely used in testing and control, and its graphical programming and display methods are suitable for system status monitoring and fault display. Fault information will interface with the database and also be stored as log files on local computers. Early warning information before faults and phenomena after faults will be displayed on the system display platform for timely review and processing by on-site observation personnel.

6. Conclusion

Astronomical telescope control systems are comprehensive technical and knowledge application systems. Establishing a reasonable and effective fault diagnosis expert system is of great significance for improving telescope reliability and thus enhancing the efficiency and quality of astronomical observations. It is an important guarantee for the safe and efficient operation of control systems. The Mini-GWAC telescope control system comprises multiple different systems with complex structures, making fault diagnosis challenging. The characteristics and innovations of this fault diagnosis system include: comprehensive system status monitoring with good coverage, display, and intelligent diagnosis processes; improved system reliability, maintainability, and usability; and guaranteed safe system operation with saved manpower and material costs.

Currently, remote telescopes are developing rapidly in China, with fully automatic control and unmanned operation becoming development directions for many telescope stations. The telescope control system fault diagnosis expert system provides strong technical support for comprehensively understanding and monitoring telescope system operation status, rapidly locating fault points when faults occur in unmanned telescopes or space telescopes. Since fault diagnosis technology has few systematic applications in China' s telescope field, this project' s research has reference significance and accumulates necessary technical experience for promoting and applying this technology to other astronomical telescope systems.

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