Design and Development of the Integrated Control System for the Quantum Science Experiment Optical Ground Station: Postprint

Authors: Wu Ying, Ge Liang, Tian Jianfeng, Jiang Xiaojun, Wang Huijuan, Wang Jianfeng, He Dong, Li Fengzhi

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Abstract

The "Micius" Quantum Science Experimental Satellite (abbreviated as "Micius") is the world' s first satellite dedicated to quantum science experiments at space scale. The "Micius" satellite, together with four quantum science experimental optical ground stations and one quantum teleportation optical ground station, constitutes a space-ground integrated quantum science experimental platform. To achieve comprehensive coordinated operation of the various ground stations, it is necessary to develop an integrated control system for quantum science experimental optical ground stations (abbreviated as the integrated ground station control system). The integrated ground station control system encompasses four quantum science experimental optical ground stations—including two newly constructed stations and two renovated stations—that require unified interface and platform control. This paper references international standard interfaces and, based on the functional requirements of quantum science experimental optical ground stations, adopts a hierarchical and modular design approach to divide the integrated ground station control system into: Web service layer, network interaction layer, and equipment control layer. The designed integrated ground station control system achieves the following functions: (1) scientific data publication; (2) internal and external data interaction; (3) parsing and execution of scientific experiment plans for the quantum science experimental satellite project; (4) monitoring of station environment and equipment status. As a unified control platform for quantum science experimental optical ground stations, the integrated ground station control system provides strong guarantee and support for the comprehensive coordinated control of quantum science experimental optical ground stations, while also serving as a general ground station control system with the advantage of being easily portable to other telescope control systems.

Full Text

Preamble

Design and Development of Comprehensive Control System for Quantum Science Experimental Optical Ground Stations

Wu Ying[1,2], Ge Liang[1], Tian Jianfeng[1], Jiang Xiaojun[1,2], Wang Huijuan[1,2], Wang Jianfeng[1], He Dong[2,3], Li Fengzhi

[1] Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China
University of Science and Technology of China, Hefei 230026, China

Abstract

The "Micius" quantum science experiment satellite represents the world' s first satellite dedicated to quantum science experiments at the space scale. Together with four quantum science experimental optical ground stations and one quantum teleportation optical ground station, Micius has established an integrated space-to-ground quantum science experiment platform. To achieve coordinated operation across all ground stations, a comprehensive control system for quantum science experimental optical ground stations (hereinafter referred to as the ground station integrated control system) was developed. This system encompasses four quantum science experimental optical ground stations—comprising two newly constructed stations and two retrofitted stations—requiring unified interfaces and platform control. Drawing upon international standard interfaces and addressing the functional requirements of quantum science experimental optical ground stations, this paper employs a layered and modular design methodology that divides the system into three distinct layers: a Web service layer, a network interaction layer, and a device control layer. The completed ground station integrated control system successfully implements four key functions: (1) scientific data dissemination, (2) internal and external data exchange, (3) parsing and execution of scientific experiment plans for the quantum science experimental satellite project, and (4) monitoring of station environmental conditions and equipment status. Serving as the unified control platform for quantum science experimental optical ground stations, this system provides robust support for comprehensive coordinated control while offering the advantage of portability to other telescope control systems as a general-purpose ground station control solution.

Keywords: Comprehensive control; Quantum science experimental optical ground station; Data interaction

1 Introduction

Traditional quantum communication based on optical fibers is fundamentally limited by intrinsic fiber losses, making it difficult to achieve transmission distances beyond the hundred-kilometer scale. Consequently, scientists have turned to free-space channels, leveraging satellite platforms to establish long-distance space-to-ground quantum science experiment platforms that enable quantum communication over much greater distances [1]. The Quantum Science Experimental Satellite project, proposed and planned by the University of Science and Technology of China, was formally approved in 2011, and the "Micius" quantum science experiment satellite was successfully launched on August 16, 2016 [1]. Supported by the Strategic Priority Program on Space Science of the Chinese Academy of Sciences, the quantum science experimental satellite project has accomplished a series of internationally leading scientific experiments and achieved highly visible scientific results [2-3].

The space-to-ground quantum science experiment platform primarily consists of the Micius satellite and the quantum science experimental satellite scientific application system (referred to as the quantum science application system). The quantum science application system comprises one center and five stations (four quantum science experimental optical ground stations and one quantum teleportation optical ground station) [4]. To fully utilize China' s vast territory and extend single-pass observable time, the quantum science experimental optical ground stations are geographically distributed across large distances. Moreover, quantum entanglement distribution experiments spanning over 1,200 kilometers require coordinated operation among multiple quantum science experimental optical ground stations [3]. To facilitate efficient and stable scheduling of quantum science experimental optical ground stations by the quantum science experiment center, a unified ground station integrated control system is essential. Several factors necessitated the specialized design and development of this system: (1) the ground stations involve numerous devices with multi-level functional requirements; (2) both the telescopes used for acquisition, tracking, and pointing (ATP) and the quantum terminals used for data acquisition are specially developed equipment lacking universal control interfaces; and (3) existing telescope control systems such as ASCOM and RTS2 [5-7] cannot meet the requirements of the ground station integrated control system. Therefore, a dedicated quantum science experimental optical ground station integrated control system was developed to achieve comprehensive control over these stations.

2 System Design

2.1 Overall Architecture

As the unified control platform for four quantum science experimental optical ground stations, the integrated control system must fulfill several critical functions: scientific data dissemination, internal and external data exchange, experiment plan parsing and execution, and monitoring and publishing of environmental and equipment status information. Given these multi-level functional requirements, the system architecture adopts a layered design approach with top-down design principles, segmenting different levels of requirements and implementing coupling through network communication interfaces to ensure a flexible and maintainable architecture.

The ground station integrated control system consists of three layers: a Web service layer, a network interaction layer, and a device control layer, as illustrated in [Figure 1: see original paper]. The Web service layer provides Web access to experiment status information and meteorological data. The network service layer primarily handles experiment plan exchange between internal and external systems, data exchange among internal components, and storage of experimental monitoring and environmental data. The device control layer parses and executes experiment plans while collecting experimental data and equipment status information. To facilitate development, the entire system is divided into four loosely coupled modules: (1) Web page display module, (2) network communication service module, (3) main control module, and (4) environmental monitoring and video surveillance module, with network communication interfaces providing coupling between modules.

The four quantum science experimental optical ground stations are geographically distant from one another. To ensure the smooth progress of the quantum science satellite project, a dedicated quantum private network was established, connecting all quantum science experimental optical ground stations and experimental nodes involved in the project. For the network layout of individual stations, connecting all device control computers directly to the quantum private network would pose security risks and create network congestion due to large data transfers. Therefore, the network layout of the ground station integrated control system employs internal-external network isolation, as shown in [Figure 3: see original paper]. The network communication server, responsible for Web publishing and external data exchange, serves as the external communication node, connecting to the quantum private network externally and to the internal network internally to facilitate data exchange between the two domains. Control hosts at the device layer (integrated control host, telescope subsystem host, quantum host, and environmental monitoring system host) are all placed within the internal network with fixed IP addresses to ensure data transmission speed and security.

2.2 Web Page Display Module

The scientific experiment center requires real-time monitoring of each quantum science experimental optical ground station' s experiment progress, equipment status, and meteorological conditions to schedule experiment plans more efficiently. To facilitate user access to information, a Web page display module was designed and developed using ASP.NET with a MySQL database, implementing a single-page mode that displays all information within one interface.

The Web page displays comprehensive information elements as summarized in , including date, epoch, UTC time, and sidereal time; current right ascension, declination, azimuth, and elevation; target right ascension, declination, and tracking errors; quantum information acquisition status, channel data, voltage, current, and half-wave plate angles; sensor temperatures, equipment status information, fault status, and post-optical-path device information; task status, beacon light status, coarse camera status, and fine camera status; all-sky cloud images, temperature, humidity, pressure, wind speed, and wind direction; and dome monitoring, observation room monitoring, and coarse/fine tracking camera video feeds.

2.3 Network Service Module

As the unified service platform for quantum science experimental optical ground stations, the integrated control system is responsible for internal and external data exchange. To address this requirement, a network service module was developed to handle data exchange with the quantum science experiment center and ground support system externally, and coordinate data exchange among internal control components internally.

To accommodate different data types and functional requirements, the network service module is divided into three components: (1) an FTP server for receiving experiment plans from the quantum science experiment center and feeding back experimental data; (2) a database for storing equipment status information, station environmental data, and experiment information; and (3) network protocol interfaces for data exchange among internal modules and between internal and external modules. As shown in [Figure 2: see original paper], the quantum science experiment center sends experiment plans via the FTP server. The control module of the main control program parses these plans and sends control commands to terminal devices through the network communication protocol between the main control software and terminal equipment, directing them to execute the experiment plans. Simultaneously, the data acquisition module of the main control software collects equipment parameters and status data, writing them to the database. Meteorological data is written to the database through the network protocol interface. Experimental data is fed back to the quantum science experiment center via the FTP server, while real-time monitoring data is sent to the ground support system through the network interface between the main control data acquisition module and the ground support system.

2.4 Main Control Module

The main control module constitutes the core of the ground station integrated control system, primarily responsible for parsing and executing experiment plans. The hardware of quantum science experimental optical ground stations –including quantum optical communication telescopes [8-9] and quantum terminals–shares similarities with astronomical telescope systems. Consequently, the main control module adopts the design philosophy of Observing Control Software (OCS), dividing the module into a device control layer and an observation strategy control layer. The device control layer comprises quantum optical communication telescope control software and quantum terminal control software. The quantum optical communication telescope control software (developed by the Institute of Optics and Electronics, Chengdu) handles acquisition, tracking, and pointing control of observation targets, while the quantum terminal control software (developed by the University of Science and Technology of China) manages quantum terminal equipment control. Based on these device control software packages, the "Quantum Science Experimental Optical Ground Station Telescope External Interface" and "Quantum Science Experimental Optical Ground Station Quantum Communication Terminal External Interface" were established. The main control software schedules equipment through these network communication interfaces to accomplish process control for quantum science experimental satellite project experiments.

Communication between the device layer and main control software employs a single-link full-duplex mode, with command control data streams and status feedback data streams transmitted independently using separate communication links. Device control terminals (quantum optical communication telescope control software and quantum terminal control software) push feedback status frames to the main control software at fixed frequencies, which parses these frames to determine equipment status and implement process control. As shown in [Figure 3: see original paper], Micius is a low-orbit satellite with high operating speeds, requiring high-frequency position and velocity control of the quantum optical communication telescope. If orbit tracking control were handled by the main control software, network communication frequency limitations and latency would prevent high-frequency, high-precision tracking control. Therefore, in this design, the quantum optical communication telescope control software is responsible for orbit tracking control. The main control software pre-converts orbit data into time-position sequences in the station coordinate system and transmits them to the quantum optical communication telescope control software. To improve efficiency, before task initiation, the main control software commands the quantum optical communication telescope to move to the first position in the orbit sequence, where it waits for the task start signal to begin orbit tracking.

2.5 Environmental Monitoring and Video Surveillance Module

The environmental monitoring and video surveillance module serves as an auxiliary component of the ground station integrated control system, providing essential support for smooth experiment execution. Station environmental information constitutes a critical reference for experiment plan formulation and adjustment, while also providing valuable context for experimental result analysis. The environmental monitoring equipment, shown in [Figure 4: see original paper], consists of an all-sky cloud camera and a meteorological station responsible for measuring and recording ground station environmental parameters. The collected information elements, summarized in , primarily include cloud cover, temperature, humidity, wind speed, and wind direction. During the initial construction phase, long-distance transmission extension cables were used to connect the cloud camera and meteorological station to the control room due to the considerable distance. However, this approach resulted in unstable communication between devices and the acquisition computer, leading to incomplete data collection. After testing and analysis, the instability was attributed to excessive cable length between the control computer and acquisition devices. The system was subsequently upgraded to employ an ARM microcontroller for controlling the all-sky camera and meteorological station and for data acquisition, with results transmitted via socket to a data reception program on the server for storage [10]. This upgrade significantly reduced failure rates during actual operation.

The video surveillance component primarily includes environmental video monitoring and coarse/fine tracking camera video feeds (referred to as coarse-fine tracking camera video). Real-time surveillance video and coarse-fine tracking camera video are captured by cameras, transmitted to digital video recorders, stored on network hard drives, and published to the quantum private network via Web access. The video surveillance module provides materials for experiment process review and reference for post-experiment result analysis.

3 System Testing and Operation

To ensure successful establishment of the satellite-to-ground quantum communication optical link after Micius' s launch, the ground station integrated control system underwent systematic testing in multiple phases following its design completion. The testing process comprised three stages: laboratory testing, low-orbit satellite simulation testing, and in-orbit testing.

Laboratory testing focused on functional verification of each module and simulated experiment flow testing, with test items and results documented in . To ensure smooth satellite-to-ground docking after Micius' s launch, experiment flow testing was required following laboratory testing. Since Micius had not yet been launched, actual observation was impossible. To simulate real observation conditions as closely as possible, low-orbit satellites were tracked for simulation testing. During the low-orbit satellite simulation phase, the ground station integrated control system was deployed at all four quantum science experimental optical ground stations, and experiment flow testing was conducted by tracking low-orbit satellites. After thorough testing, the system successfully supported pre-launch testing at all four stations. Following Micius's launch, in-orbit testing commenced with actual tracking of the satellite. During this phase, the Xinglong quantum science experimental optical ground station achieved the first successful docking with Micius, followed by successful docking at the remaining stations. After all four quantum science experimental optical ground stations had successfully docked with Micius, the ground station integrated control system entered regular operation.

[Figure 5: see original paper] and [Figure 6: see original paper] illustrate the Web display page and main control software interface during regular operation. The Web page provides real-time display of experiment information, environmental data, and surveillance video, while the main control software implements experiment plan parsing and execution, collection and recording of experiment data and equipment status, and includes stellar observation capabilities.

4 Summary and Outlook

The designed ground station integrated control system has successfully enabled automated control of quantum science experimental optical ground stations, allowing observers to perform observation tasks after minimal training. Deployed across all four quantum science experimental optical ground stations, the system has served the satellite-to-ground high-speed quantum key distribution experiment [2] and the quantum entanglement distribution experiment over 1,200 kilometers [3], successfully fulfilling its mission in the quantum science experimental satellite project. Currently, the environmental monitoring module operates independently from the observation control system and does not automatically adjust experiment plans when weather conditions change abruptly. Future work will focus on implementing dynamic observation plan adjustments based on meteorological information to achieve highly automated observation control and further improve observation efficiency.

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