Overview of the Telescope Observation Management and Control System Bus

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ABSTRACT

With the continuous advancement of astronomical observation technology, the design of modern telescopes is increasingly inclined towards high precision, high automation, and intelligence. As one of the core components to achieve these goals, control bus technology plays a crucial role. This paper provides an overview of the relevant technologies of telescope control buses, focusing on their system architecture, common communication protocols, and application scenarios. The basic architecture of telescope control buses is analyzed, including the selection of communication buses, hardware interfaces, and data flow management. Furthermore, commonly used communication protocols in current telescope systems, such as VME bus, EtherCAT bus, CAN bus, Fiber Channel bus and Macro bus, are introduced. Their advantages and disadvantages in terms of real-time performance, reliability, and bandwidth are evaluated. Finally, the practical applications of telescope control buses in areas such as pointing control, tracking accuracy, and system integration are discussed. This paper summarizes bus control technology development trends and provides insights into the innovation and challenges of future telescope control bus technology.

Keywords: VME Bus, EtherCAT Bus, CAN Bus, Fiber Channel Bus, Macro Bus, Real-Time Data Transmission, Telescope Control System

1. INTRODUCTION

The telescope observation management and control system is a critical component of modern astronomical telescopes, responsible for coordinating various hardware devices (such as optical components, motion control systems, sensors, etc.) as well as functions like data processing, storage, and transmission[1-5]. As the scale and complexity of telescopes continue to increase, the coordination and communication between different components within the system have become increasingly complex. To ensure efficient operation, precise observation, and rapid response, employing efficient and reliable data transmission and communication methods is essential.

The telescope observation management and control system acts as the "brain" of the telescope, directing the coordination of its functional components to complete observation tasks. The design focuses on the high precision, distribution, real-time performance, reliability, security, and openness of the telescope control system. Standardized and open electronic devices are used to construct the telescope control system in a modular fashion. Given the long lifespan of telescopes and the rapid pace of control system component updates, this approach to constructing the control system helps shorten development cycles while also facilitating system maintenance and upgrades[6-9].

In this context, bus technology, as a communication architecture, can efficiently enable interconnection and data transmission between different devices within the telescope control system. The bus simplifies the interoperability between different hardware components by providing a unified communication interface and protocol, ensuring that the entire system operates smoothly in environments with high real-time and stability requirements[10-15]. The bus not only enables real-time control between devices but also effectively manages the transmission and storage of large amounts of observational data, ensuring the efficiency and accuracy of the telescope when performing complex observation tasks.

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This paper aims to review several commonly used bus technologies in telescope control systems, exploring their specific applications, advantages, and disadvantages within the system. By comparing different types of bus architectures, the paper analyzes their adaptability and strengths in various scenarios, further clarifying the important role of the bus in telescope control systems and providing theoretical references for bus selection and optimization in future telescope control system designs.

2. OVERVIEW OF TELESCOPE CONTROL SYSTEM

The telescope control system is the core technological platform for astronomical observation and data processing, encompassing the entire process from observation task planning to data acquisition[16-18], processing[19-21], storage, and analysis. Modern telescope control systems are typically composed of multiple modules, with each module responsible for specific tasks, ensuring that the system operates stably and efficiently under various observation conditions[22-24].

The system includes the Telescope Control Subsystem (TCS), Observation Control Subsystem (OCS), Remote Control Subsystem (RCS), Environmental Control Subsystem (ECS), and Dome Control Subsystem (DCS). The TCS control system consists of the Mount Control (TCS-Mount) and Focal Plane Control (TCS-FocalPlane), responsible for driving and controlling all the mechanical components of the telescope, pointing, tracking[25-28], and calibration, as well as communication within the internal subsystems and with other subsystems. The design emphasizes reliability while ensuring accuracy. The OCS observation subsystem enables fully automated observations based on the observation plan and records relevant data. The RCS remote control subsystem allows complete control of the telescope and the tracking dome via the Internet, enabling remote observations[29-31].

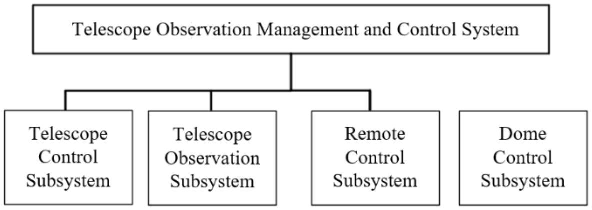

Figure 1. Telescope Control System Diagram.

2.1 Basic Functions of the Telescope Control System

The functions of the telescope control system are achieved through the collaboration of various components of the telescope. It receives commands from the upper-level operational control system and simultaneously collects environmental data from the environmental system. When the environmental data meets the operational conditions for the telescope, the system coordinates the Dome Control System to open the dome and orient it toward the target celestial object as instructed. At the same time, it controls the movement of the telescope's mechanical components, directing the telescope to point at and track the target celestial body.

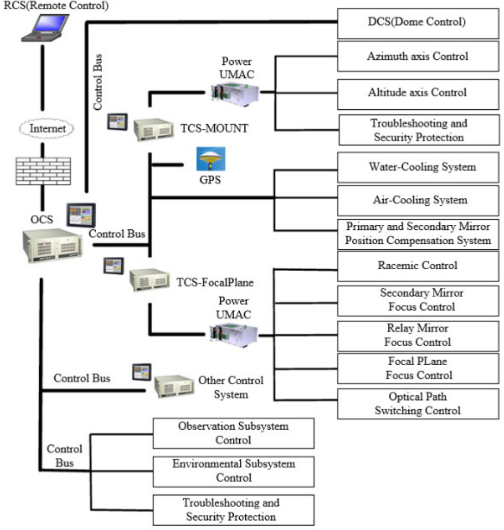

Figure 2. Telescope Control Structure.

The data acquisition system is responsible for converting the raw data obtained during astronomical observations into a processable format. This includes image data[32-35], spectral data[36-37], and other sensor data, which are crucial for scientific analysis. The data acquisition system typically includes sensors, cameras, spectrometers, and other devices, which need to be connected to the control system in real-time using bus technologies.

The device control module coordinates various hardware components of the telescope, such as optical elements (lenses, filters, etc.), detectors, and cooling systems. It ensures that these devices operate according to predetermined parameters and precision during observations. Control signals for each device, status monitoring, and fault diagnosis are managed through data exchange on the system's bus[38-40].

The telescope typically requires high-precision attitude control and positional adjustments. The motion control system ensures the telescope can point to the specified celestial body by precisely controlling the axes (such as azimuth and altitude) [41-43]. To ensure accuracy, the motion control system relies on real-time data and feedback signals, which are transmitted via the bus to ensure synchronized coordination of the components.

Astronomical observations generate vast amounts of data, making data processing and storage essential tasks within the telescope control system. The data processing system is responsible for real-time processing, analysis, and generation of scientific products from the acquired data. The data storage system ensures the reliable preservation of observation data for later analysis and research. The large volume of data transfer and coordination during the data processing and storage process is typically managed through a high-bandwidth, high-reliability bus system.

2.2 The Role of the Bus in the Telescope System

In the telescope control system, bus technology plays a critical role as a communication intermediary. Its primary function is to provide an efficient and stable communication channel between different devices within the system, ensuring real-time data transmission and synchronized operation of the devices[44-47].

In a telescope control system, various devices such as sensors, motion controllers, and data acquisition equipment are typically interconnected via a bus. The bus provides a unified data transmission channel, enabling fast and secure exchange of information between different devices. For example, control signals, status data, and observation data are transmitted through the bus to relevant components, facilitating the collaborative operation of the system. Devices in the telescope control system need to be precisely coordinated to ensure the smooth execution of observation tasks. Through the bus, devices can share their status information in real time and perform coordinated operations. For instance, when the motion control system needs to adjust the telescope's attitude, it must receive real-time feedback from the data acquisition system or positioning sensors via the bus to make precise adjustments[48-50]. As the telescope system expands and its functions increase, the bus architecture can easily support the integration of new devices. For example, new detectors or sensors can be easily integrated with the control system via the bus, without requiring significant modifications or restructuring of the entire system. The flexibility and scalability of the bus architecture allow the system to be gradually upgraded in line with technological advancements. Telescope control systems often need to handle real-time tasks such as tracking celestial bodies and adjusting the telescope's orientation. The selection and optimization of the bus directly affect data transmission delays and the system's real-time responsiveness[51-52]. Therefore, when designing a telescope control system, it is essential to choose a high-bandwidth, low-latency bus technology to meet the system's stringent real-time requirements.

Bus technology in the telescope control system not only fulfills the fundamental function of data transmission between devices but also plays a crucial role in ensuring the system's stability, scalability, and real-time performance. Through the bus, various components can collaborate efficiently, ensuring that the telescope operates stably and precisely while performing complex observation tasks.

3. BUS TYPES AND APPLICATIONS IN TELESCOPE CONTROL SYSTEMS

3.1 VME Bus

The VME bus[53-57], first introduced by Motorola in 1981, is a standard bus for embedded computer systems. It supports high-bandwidth data transmission, modular design, and offers high reliability and scalability, making it widely used in aerospace, industrial control, and scientific instrumentation[58-61]. The Very Large Telescope (VLT) employs the VME bus to connect and control various components of the telescope, particularly in data acquisition and real-time control scenarios.

The VLT, one of the world-leading astronomical observation facilities owned by the European Southern Observatory (ESO), consists of four 8-meter telescopes and multiple scientific instruments, aimed at high-precision astronomical observations[62-65]. To ensure the efficient operation of the telescope, the VLT control system must handle complex tasks, including real-time data acquisition, system status monitoring, and optical system control. As a mature hardware communication standard, the VME bus plays a key role in the control system.

Figure 3. VLT Telescope.

3.1.1 Basic Principles and Characteristics of the VME Bus

The VME bus is a multipoint communication-based bus structure that features high bandwidth, flexible scalability, and excellent real-time performance. It consists of multiple modules, each including a processor, input/output (I/O) interfaces, memory, and communication modules. These modules are interconnected via the bus, enabling system expansion and upgrades. The VME bus supports data transfer rates ranging from several megabits to several hundred megabits per second, making it suitable for high-bandwidth applications such as image processing and data acquisition[66-69]. The VME bus supports high real-time data transmission, making it ideal for high-precision control systems. Its redundant design and anti-interference capabilities have led to its widespread application in industrial and scientific fields. The VME bus supports large-scale device expansion, allowing multiple devices to connect to the host, thereby forming a distributed system. Furthermore, the VME bus is compatible with a variety of hardware platforms, including processors, I/O modules, and storage modules, which makes it highly adaptable in various embedded systems[70-71].

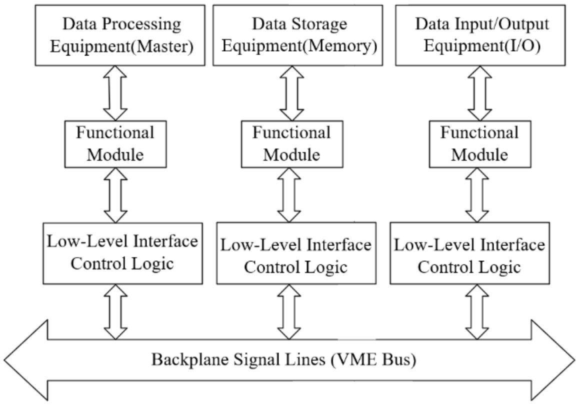

Figure 4. General System Architecture of the VME Bus.

3.1.2 Application of the VME Bus in the VLT Control System

In the VLT telescope, the VME bus is primarily used for data acquisition and sensor integration. The VLT telescope is equipped with numerous sensors to monitor various physical parameters of the telescope, such as temperature, pressure, position, and angular velocity. The analog and digital signals generated by these sensors are transmitted via the VME bus to the central processing system for analysis and processing. With the high-speed data transmission of the VME bus, the system can obtain real-time status information from various components and respond promptly[72-74].

The VME bus is not only used for data acquisition but also plays a key role in the precision control systems of the VLT. For instance, the mechanical components of the VLT, such as the electric telescope tube and optical lens positioning systems, require precise motor control signals. Control modules connected via the VME bus can quickly transmit commands and provide real-time feedback on the device's status, ensuring the coordinated operation of all components[75-77]. This is particularly crucial during real-time adjustments of the optical system, where the high real-time performance of the VME bus is vital.

The telescope's position control and tracking system is a critical component of the VLT control system. This system requires precise control of the telescope's azimuth and altitude axes to ensure the telescope always points to the correct celestial body. In this process, the VME bus provides high-speed, low-latency data transmission support. Through the

VME bus, the control system can receive real-time position data from the telescope and match it with control commands, thereby adjusting the telescope's attitude.

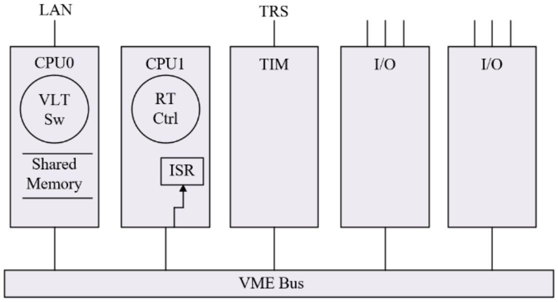

Figure 5. Example of multi processor tac application using standard VLT components.

Figure 5 shows the architecture of a typical tac application[78]. In this example tac has been deployed on two PPC CPU boards, where one of the boards is assigned exclusively to the real-time control algorithm. CPU0 implements the standard VLT interface using components from the ESO common software. This CPU also holds the shared memory used to implement bidirectional communication channels between the two CPUs based on message queues. CPU1 runs one application task, the real-time controller, which is responsible for processing requests from the tac server running on CPU0 and for managing the periodic execution of the control algorithm implemented as an interrupt service routine (ISR) and triggered by the time reference system. In order to avoid non deterministic resolution of concurrent bus accesses, the shared memory is located on CPU0 and all IO are exclusively dedicated to the tac RT algorithm, leaving VME bus under complete control of CPU1.

The VLT telescope requires the coordination of multiple subsystems to perform complex task scheduling and real-time operations. As the core communication medium, the VME bus ensures the efficient execution of task scheduling. Through the VME bus, the control system can quickly respond to various operation requests and automatically execute astronomical observation tasks. The high reliability and scalability of the bus make this process more efficient and stable.

3.2 EtherCAT Bus

EtherCAT is a real-time communication protocol based on the standard Ethernet protocol, originally proposed by Beckhoff Automation in Germany, and widely used in industrial automation and control systems[79-82]. Compared to traditional Ethernet communication methods, EtherCAT provides more efficient and real-time performance through optimized protocols and transmission mechanisms, making it suitable for applications requiring high speed and precise synchronization.

With the continuous development of modern radio astronomy technologies, the complexity and data volume of radio telescope systems have been increasing, requiring higher data transmission rates, greater system integration, and more reliable communication protocols. The Atacama Large Millimeter/submillimeter Array (ALMA) is currently one of the most advanced radio telescope arrays in the world, located in the Atacama Desert in Chile[83-85]. ALMA's design and construction are aimed at studying the radiation of astronomical objects in the millimeter and submillimeter wavelengths, exploring the origin and evolution of the universe.

ALMA consists of 66 antenna units, and the antenna array operates collaboratively using a variety of high-performance technologies, including the EtherCAT bus[86-87]. As a mature high-speed network communication technology, EtherCAT plays a crucial role in ALMA's system architecture, primarily used for efficient data transmission, remote control between devices, and efficient system integration.

Figure 6. Atacama Large Millimeter/submillimeter Array.

The study in reference 88 takes the ALMA control system as an example[88]. It compares the current architecture with the new design that is not only compatible with the existing hardware devices of ALMA but also provides the foundation for the new subsystems associated with ALMA 2030 initiatives. The progress of a proof of concept is reported, which explores the possibility of embedding the existing ALMA monitor and control data structure into EtherCAT frames, using EtherCAT as the primary communication protocol to monitor and control hardware devices of ALMA telescope subsystems.

3.2.1 Basic Principles and Characteristics of the EtherCAT Bus

EtherCAT differs from traditional Ethernet protocols by adopting a chain-based transmission method. Data is sent from the master station to the first slave station, and as it passes through each slave, the data is read and processed according to a predefined format[89-90]. Each slave only needs to read the data relevant to it and then forward the data packet to the next slave, ultimately reaching the next node or returning to the master station. The master station does not wait for each slave to complete data processing before continuing transmission; instead, it efficiently circulates the data packets, significantly reducing communication latency.

EtherCAT adheres to Ethernet standards and supports various topologies, including linear, star, and tree configurations, propagating in a "logical closed-loop" manner. This flexibility allows it to adapt to control systems with different scales and functional requirements. The master station implementation requires only a standard network card, with no need for switches or routers, addressing issues such as switch latency, stack delays, and bandwidth utilization in traditional Ethernet. This results in more stable network connections and greatly enhances the system's fault tolerance.

In EtherCAT, the master station sends a large data frame, and each slave station only reads the part of the data packet it is responsible for, passing the remaining portion to the next node. This mechanism not only greatly reduces communication delay but also decreases the data processing load on the slaves, improving the overall system efficiency. EtherCAT is particularly suited for real-time systems because it allows large volumes of data to be transmitted within specific time windows while providing extremely low latency. The master and slave stations are synchronized through a precise timing mechanism, ensuring the real-time transmission of data, allowing the control system to operate under high-precision requirements[91-92].

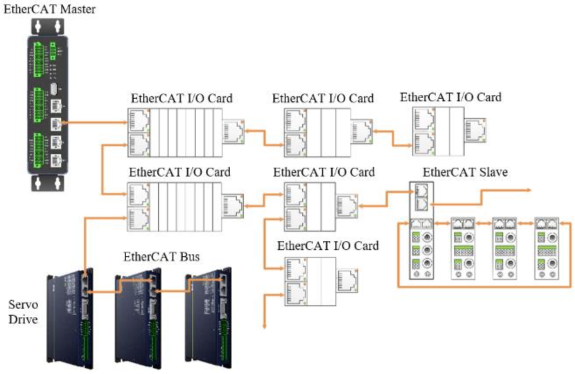

Figure 7. EtherCAT Topology Diagram.

3.2.2 The Application of the EtherCAT Bus in the ALMA Control System

The antennas of the ALMA telescope require precise pointing control and synchronized operation. To ensure that the antennas remain accurately aligned with the target during observations, the control system needs to process large amounts of data in real-time and quickly transmit commands. Since EtherCAT can complete data exchange within microseconds, the master station (control center) can issue control instructions to each antenna in a very short time, ensuring the antennas respond swiftly and make precise adjustments. Multiple antennas in the ALMA system need to work in coordinated operation with extremely precise time synchronization, particularly during array observations and interferometric measurements. The high-precision time synchronization provided by EtherCAT ensures that the operations of the antennas are accurately aligned, avoiding observational errors caused by time discrepancies.

In the ALMA telescope's operations, each antenna not only needs to perform positioning control but also needs to collect celestial signals and transmit the data to the data processing system. Each antenna of ALMA is equipped with high-performance receivers and signal processors, generating a massive amount of data[93-94]. The high bandwidth and low latency characteristics of EtherCAT ensure that these antennas can quickly transmit the collected signal data to the data processing unit for further processing. Meanwhile, the efficient communication mechanism of EtherCAT also reduces delays in data transmission, ensuring the system's real-time performance. The ALMA telescope array consists of multiple antennas, and each antenna needs to synchronize and transmit large amounts of data during observations. EtherCAT's chain transmission mechanism ensures that these data can be efficiently transmitted to the data center without placing excessive strain on network bandwidth[95-96].

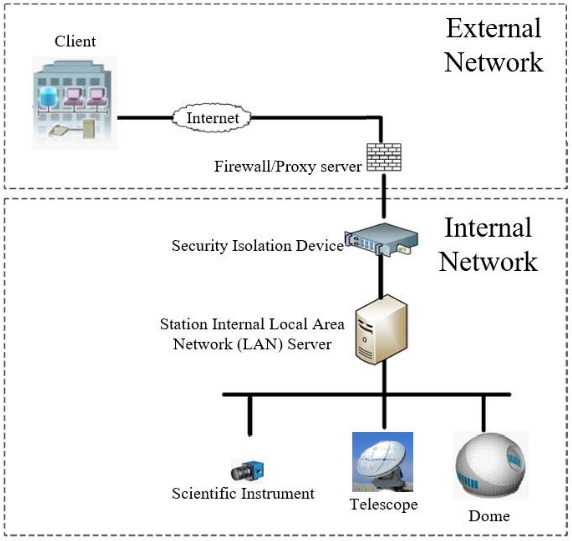

Figure 8. Network architecture diagram.

3.3 CAN Bus

The CAN bus is a highly reliable, interference-resistant protocol with real-time communication capabilities, making it particularly suitable for device control and data exchange in embedded systems[97-100]. Many large astronomical telescopes use the CAN bus as their key communication protocol. The Subaru Telescope, a large optical/infrared telescope with an 8.2-meter primary mirror, is equipped with multiple scientific instruments and auxiliary optical systems. Located on the Haleakalā mountain in Hawaii, it is a world-class astronomical observation facility that utilizes the CAN bus to coordinate and manage the operation of multiple subsystems, including mechanical drives, optical adjustments, and sensor data acquisition[101-103].

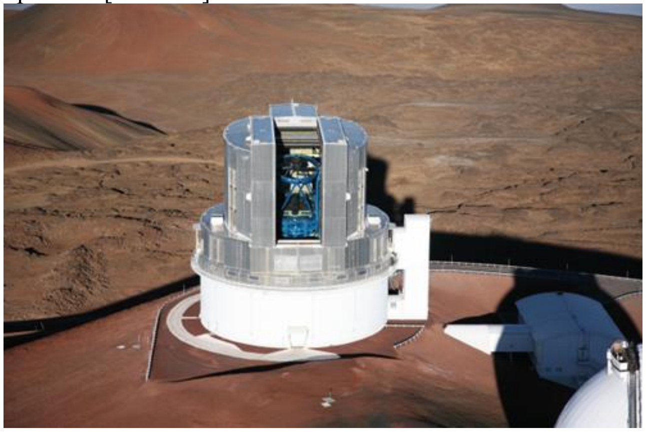

Figure 9. Subaru Telescope.

3.3.1 Basic Principles and Characteristics of the CAN Bus

The CAN bus adopts a multi-master communication mode, meaning that each node in the network can independently initiate communication without the need for a master-slave mode or central controller management. Each node communicates with the bus via a pair of differential signal lines (typically CAN_H and CAN_L), and this differential signal transmission method effectively resists electromagnetic interference, ensuring the reliability of data transmission[104-106]. During data transmission, the CAN bus performs a check on each data frame to ensure data accuracy. Common error detection mechanisms include bit error detection, CRC checks, and acknowledgment error detection. If an error occurs during transmission, the sender will retransmit the data until it is successfully received, ensuring reliable communication.

The CAN bus supports half-duplex communication, meaning that at any given time, any node in the network can only transmit data but cannot receive it. Since it operates in a multi-master mode, any node can initiate communication at any time, making it ideal for dynamic, distributed control systems. To ensure accurate data transmission, the CAN bus detects errors and employs an automatic retransmission mechanism to prevent data loss.

The CAN bus adopts a bus topology, where all nodes are connected via a pair of twisted-pair wires (CAN_H and CAN_L). The topology is simple, easy to expand, and maintain. Each node is connected to the bus via this twisted pair and communicates through the bus[107-108].

The CAN data bus consists of two lines, a yellow CAN_High and a green CAN_Low[109-110]. When no data is being transmitted, both lines are at the same voltage level of 2.5V, known as the recessive level. When a signal is transmitted, the CAN_High voltage level increases by 1V to 3.5V, and the CAN_Low voltage level decreases by 1V to 1.5V. When the difference between CAN_H and CAN_L is less than 0.5V, it is recessive, and the logic signal is "logical 1" – high level. When the difference between CAN_H and CAN_L exceeds 0.9V, it is dominant, and the logic signal is "logical 0" – low level.

The CAN controller converts the signals from the CPU into logical levels (i.e., logical 0-dominant level or logical 1 -recessive level). After the CAN transmitter receives the logical level, it converts it into a differential level and outputs it to the CAN bus, as shown in Figure 10. The CAN receiver converts the differential levels on the CAN_H and CAN_L lines into logical levels and outputs them to the CAN controller. The CAN controller then converts the logical level into the corresponding signal and sends it to the CPU, as shown in Figure 11. This structure is highly suitable for distributed control and large-scale systems, as it reduces wiring complexity while ensuring high-speed data transmission.

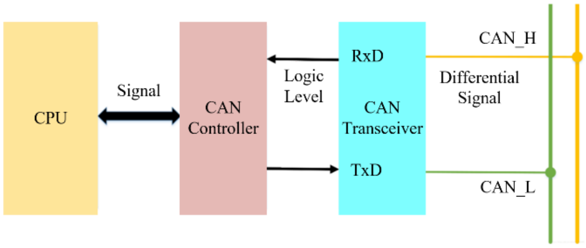

Figure 10. Signal Transmission Process.

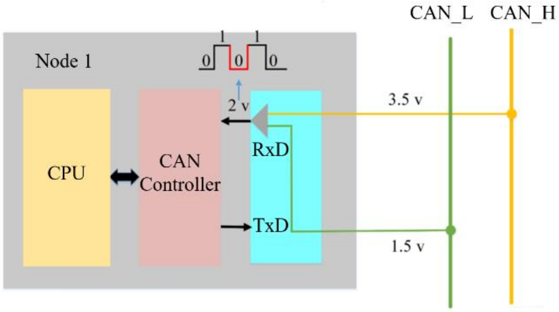

Figure 11. Signal Reception Process.

Its priority-based arbitration mechanism ensures low latency and high response speed. Since message transmission in the CAN bus is based on priority, high-priority messages are transmitted first when they arrive, ensuring the timely execution of high-priority tasks. The CAN bus uses differential signal transmission, which provides strong immunity to electromagnetic interference (EMI), effectively reducing the impact of external noise while improving signal stability.

3.3.2 The Application of the CAN Bus in the Subaru Control System

In the Subaru Telescope, the mechanical control system is responsible for the precise positioning and tracking of the telescope to ensure accurate alignment and continuous observation of celestial objects. The CAN bus is widely used in various mechanical drive units, such as the altitude and azimuth drive systems of the telescope. These drive systems communicate with the main control computer via the CAN bus, receiving positioning commands in real time and controlling the movement of the servomotors. Due to the high precision requirements of the telescope, the mechanical control system must have a high real-time response capability. The real-time communication capability of the CAN bus ensures that the system can receive and process control commands within microseconds, allowing the telescope to align accurately with targets and maintain stable long-term tracking. Additionally, the CAN bus supports distributed control of multiple drive units, simplifying the integration of complex mechanical systems.

The adjustment of the optical system is a crucial part of the Subaru Telescope, involving the automatic alignment and adjustment of optical elements such as the primary mirror, spectrometers, and filters[111-113]. The CAN bus plays a role in real-time control and data transmission during this process. For example, when adjusting the curvature and shape of the primary mirror, the CAN bus connects multiple fine-tuning drive units, ensuring that each drive unit can respond quickly and adjust the mirror surface. Through the CAN bus, the optical system can automatically adjust based on real-time feedback signals, optimizing image quality. In the routine maintenance of the optical system, the CAN bus also supports remote diagnostics and control, ensuring that the equipment remains in optimal working condition.

The Subaru Telescope is equipped with multiple sensors to monitor its operating status and environmental conditions. These sensors include temperature, humidity, and vibration sensors. The CAN bus collects data from these sensor nodes and transmits it to the main control system for analysis. For example, temperature and humidity sensors transmit environmental data in real time via the CAN bus, allowing the control system to adjust the telescope's operating mode based on environmental changes. The high reliability and anti-interference capability of the CAN bus ensure the accuracy of the data, especially in complex external environments, where the use of the CAN bus avoids data loss or delays that may occur with traditional serial communication protocols.

Since the Subaru Telescope typically requires long observation times and is often operated remotely, another important application of the CAN bus is remote control and fault diagnosis. Through the CAN bus, technicians can remotely access individual control units, adjust device settings, and perform maintenance operations. Moreover, the fault tolerance of the CAN bus allows the system to continue operating normally even if some nodes fail. In the event of a system failure, the CAN bus can transmit error information promptly, helping engineers quickly locate the source of the fault and carry out repairs, minimizing telescope downtime.

3.4 Fiber Channel Bus

FC (Fiber Channel) is a high-speed serial transmission bus proposed in 1988 by the X3T11 group of the American National Standards Institute (ANSI), addressing the technical bottlenecks encountered by the parallel bus SCSI. It can be understood as similar to TCP/IP in SAN, following the OSI seven-layer model. Its core goal is to provide high bandwidth, low latency, and high reliability network connections to support high-speed data transmission between numerous storage devices, servers, and computer systems[114-116].

It is also applied in the Keck Observatory, particularly for data transmission between multiple instruments and the high-precision observation requirements. The Keck Observatory, located on Mauna Kea in Hawaii, is one of the most advanced optical and infrared telescopes in the world. It consists of two 10-meter primary mirrors, offering extremely high resolution and sensitivity. The Keck Observatory uses fiber optic bus technology to support the coordination of its multiple observation systems, especially in complex operations such as high-resolution imaging, spectral observation, and interferometric imaging. Due to the high bandwidth and real-time data transmission requirements of these systems, fiber optic bus technology provides advantages such as high bandwidth, low latency, and resistance to electromagnetic interference, ensuring the efficient and reliable operation of the various devices.

Figure 12. Keck Telescope.

3.4.1 Basic Principles and Characteristics of the Fiber Channel Bus

The design principle of Fiber Channel is to connect multiple devices via high-speed optical fiber and copper cables, providing an efficient and low-latency data transmission channel[117]. Its key characteristics are as follows: high bandwidth, multi-media, and long-distance transmission: the serial transmission rate has increased from the initial 1Gbps to 4Gbps and is continuing to evolve towards higher speeds and greater data throughput, suitable for large-scale data exchange between different modules (e.g., audio and video data streams); reliability and real-time performance: various error handling strategies, 32-bit CRC checks, prioritization to accommodate different message requirements, and resolution of conflicts during medium access control, with a transmission error rate below 10^-12 and end-to-end transmission delay of less than 10 microseconds, supporting non-acknowledged mode and sensor data transmission; uniformity and scalability: nodes can be easily added or removed to meet different application needs, with flexible topology supporting multi-level system interconnections. High-level protocol mappings enhance compatibility and adaptability. Protocols such as SCSI, IP, and ATM can be mapped onto Fiber Channel to effectively reduce the variety of physical devices and additional equipment, thus lowering economic costs; open interconnection, adhering to unified international standards.

Fiber Channel (FC) is a high-throughput, low-latency, packet-switched, and connection-oriented network technology. The entire standard series is continuously evolving, and within the aerospace field—Aerospace Electronic Systems Environment Engineering (FC-AE)—protocol specifications have been customized into five types: unsigned anonymous message transmission (FC-AE-ASM), MIL-STD-1553 high-level protocol (FC-AE-1553), virtual interface (FC-AE-VI), FC lightweight protocol (FC-AE-FCLP), and Remote Direct Memory Access protocol (FC-AE-RDMA) [118-120].

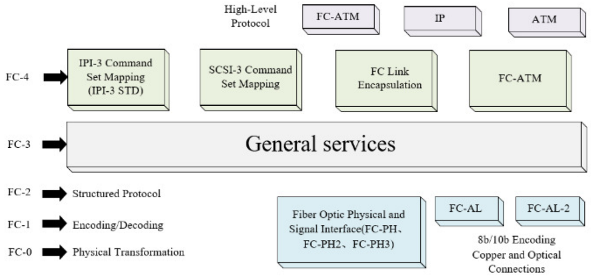

Figure 13. FC 5-layer protocol.

In the diagram, FC-0: Interface to connect physical media, cables, etc., defines the standards for encoding and decoding. It specifies various media and associated drivers and receivers that can operate at various rates; FC-1: Transmission protocol layer or data link layer, encoding or decoding signals. This encoding scheme separates control bytes from data bytes and simplifies bit, byte, and word synchronization; FC-2: Network layer, the core of Fiber Channel, defines frames, flow control, and quality of service; FC-3: Defines common services, such as data encryption and compression, shared by multiple N-ports of a Fiber Channel node; FC-4: Protocol mapping layer, defines the interface between Fiber Channel and upper-layer applications, such as serial SCSI protocols.

Fiber Channel supports various topologies, including point-to-point, Arbitrated Loop (AL), and Switched Fabric (FC-SW), which can be flexibly selected based on different application scenarios. Among the three topologies, Switched Fabric (FC-SW) offers the most powerful functionality, highest reliability, best performance, and largest bandwidth, supporting up to 16 million devices[121-122]. It ensures efficient, low-latency communication between multiple control computers and sensors, making it ideal for complex large-scale telescope control systems. Point-to-point topology (P2P) is suitable for smaller, simpler control systems, connecting two devices for efficient data transfer. In large telescope systems, Switched Fabric topology enables the connection of multiple control devices and sensors, supporting large-scale data transfer and efficient device management.

Fiber Channel typically uses fiber optics as the transmission medium, offering stronger electromagnetic interference (EMI) resistance compared to traditional copper cables, ensuring that signals are not interfered with during long-distance transmission. Fiber optics are non-conductive, making them safer and more stable in environments prone to lightning, particularly suitable for high-reliability astronomical observations. Fiber optics provide extremely high bandwidth, supporting large data volumes. Modern fiber optic systems can easily support transmission rates of 10Gbps, 100Gbps, or even higher. Fiber optics have low loss and low latency, making them ideal for high-speed, real-time data transmission. This is critical for real-time feedback and precise control in telescope systems. The transmission loss of fiber optics is very low, especially in single-mode fiber, where signal degradation is minimal over distances of several tens of kilometers. This makes fiber optic buses particularly advantageous for long-distance communication. They are well-suited for remote operation: fiber optics can effectively support remote control and monitoring systems, especially in scenarios like astronomical telescopes, which require remote operation and data transmission. Fiber optic buses provide ultra-low latency, typically in the microsecond range, ensuring that the telescope system can respond and adjust in real-time.

3.4.2 The Application of the Fiber Channel Bus in the Keck Control System

The Keck Observatory is equipped with various optical and infrared observation instruments, such as spectrometers, imagers, and other high-precision detectors. When these instruments operate simultaneously, they generate large amounts of data. To ensure synchronization and efficient data transmission, fiber optic buses are used to connect these instruments to the central control system. For example, the fiber optic bus supports the transmission of high-resolution image and spectral data from spectrometers and imagers, with data sizes potentially reaching several hundred megabytes or more. The high bandwidth of fiber optics ensures that this data can be efficiently transmitted from the telescope to the data processing center.Real-time data transmission and processing: The low latency of fiber optic buses allows observational data obtained from multiple instruments to be transmitted in real-time to the control console or data processing system. This is crucial for real-time adjustments to observational parameters and optimization of observational conditions[123].

The Keck Observatory also utilizes fiber optic buses for interferometric observations, particularly in the Keck Interferometer, where multiple telescopes need to work together to perform high-resolution astronomical imaging. Interferometer signal synchronization: The Keck interferometer system connects multiple telescopes via fiber optic buses to achieve high-precision signal synchronization. This synchronization is critical, as during interferometric observations, the observational data from multiple telescopes need to be precisely synchronized to synthesize a higher-resolution image. The fiber optic bus provides accurate time synchronization, ensuring that the signals from each telescope are not distorted due to delays or time differences.Data transmission for interferometric observations: During interferometric observations, the data collected by multiple telescopes is transmitted in real-time to the central processing system via fiber optic buses. The high bandwidth of fiber optics enables these data to be transmitted without distortion, ensuring the accuracy of the observational results.

When conducting nighttime observations, the operators at the Keck Observatory do not necessarily need to be present at the telescope. Through fiber optic buses, the various devices of the telescope can be remotely controlled and monitored, even from a global distance. The Keck Observatory uses the fiber optic network for remote control of multiple devices. This control system allows commands to be transmitted to the observation instruments via the fiber optic bus, while also receiving feedback. This not only enhances operational efficiency but also enables observation and data analysis over the network[124]. Additionally, fiber optic buses are used for real-time monitoring of the telescope system, such as monitoring the status of the telescope, detecting any potential faults or anomalies, and ensuring that the telescope operates at optimal performance.

3.5 Macro Bus

The Macro Bus (Motion and Control Ring Optical Bus) is a real-time communication bus specifically for high-performance motion control systems developed by Delta Tau Company. It adopts a master-slave structure and connects the main controller (such as Power PMAC) with multiple distributed devices (such as servo drivers, I/O modules, encoder interfaces, etc.) through the optical fiber ring network. It features high speed, low latency, strong determinism and high synchronization accuracy.

The Macro bus supports a fully synchronous data refresh mechanism, which can achieve data synchronization and command distribution between the controller and all nodes within a fixed period. It is widely used in systems with extremely high requirements for multi-axis collaborative control, especially suitable for high-precision, large-inertia, and multi-motor collaborative drive scenarios. Its fault-tolerant design allows the system to continue operating when the single-channel optical fiber is disconnected, improving the stability and reliability of the system.

In practical applications, the Macro bus has been used in several internationally renowned large telescope projects. For example, in the Solar Telescope Upgrade Program (DKIST) of the National Optical Observatory (NOAO) of the United States, a communication architecture based on the Power PMAC controller and Macro bus was adopted, achieving high-precision synchronous control of the optical platform and the turntable[125-128]. The Macro bus holds significant value in high-end fields such as the spindle control of large telescopes, open-loop/closed-loop trajectory execution, and racemization axis synchronization. It is a key technology that is difficult to be replaced by traditional buses like CAN and EtherCAT.

Figure 14. DKIST Telescope.

3.5.1 Basic Principles and Characteristics of the Macro Bus

Macro is a real-time motion and machine control network in a ring configuration. It is an open protocol with many vendors providing compatible components. It is built around 100 megabit-per-second Ethernet technology (125 Mbit/sec with error correction bits) for high-speed transfers around the ring, minimizing transport delays. Most commonly used is fiber-optic transmission between stations on the ring, which provides complete noise immunity and the capability for long transmission between stations[129-130].

Macro is a master/slave network. Power PMAC is most commonly used as a master on the ring, sending commands to slave servo drives, I/O modules, and other peripherals on the ring, and receiving feedback values from them. However, it is possible to configure Power PMAC as a slave device on the ring, and for its motors to be set up to accept cyclic servo commands over the ring. This permits a single Power PMAC (the master) to compute all of the coordinated tasks, but to distribute the individual motor tasks such as servo-loop closure and motor commutation, and the hardware, across the ring.

The Power PMAC Etherlite is a compact and cost-effective configuration intended for control through industrial networks and fieldbuses. It consists of a Power PMAC CPU board, a network interface board that can be configured for the MACRO fiber optic network, the EtherCAT electrical network, or both. Optionally, a fieldbus interface board for buses such as Profibus, DeviceNet, or CCLink can be installed.

Figure 15. Power PMAC Etherlite Controller.

3.5.2 The Application of the Macro Bus in the DKIST Control System

In DKIST, the world-leading solar observation platform, the Macro bus is used as the core motion control communication architecture to coordinate the real-time communication between the main control system and multiple distributed servo execution modules. DKIST features a complex mechanical structure, including an azimuth axis, an altitude axis, a racemization axis, an optical platform, a focusing unit, and multiple adjustable lens groups. These moving parts need to operate synchronously at high precision to ensure stable tracking of solar targets and support multiple scientific observation modes. The Macro bus builds a closed-loop communication network through high-speed optical fibers, enabling the controller to distribute motion instructions to all key nodes and synchronously collect feedback data within millisecond-level cycles, achieving precise coordination of the entire telescope system.

In terms of hardware deployment, DKIST adopts Macro bus connection module cards, covering multiple functional areas such as servo amplifier control, feedback encoder acquisition, and I/O event response. Especially in large-inertia systems such as optical platforms and height axes, multiple high-power servo units are connected through the Macro bus, enabling the controller to uniformly schedule the current loop, speed loop and position loop, and achieve complete synchronization of multiple axes within the same period, meeting the dual requirements of the system for stability and responsiveness. In addition, the redundant ring structure of the Macro bus ensures that the system maintains communication capabilities even when some optical fiber links are damaged, significantly enhancing the reliability of the telescope's operation and its continuous observation capability.

More importantly, the Macro bus supports a precisely synchronized global clock mechanism, which is used in DKIST to ensure the time coordination of various active optical adjustment mechanisms and tracking mechanisms. For example, when conducting rapid solar surface scanning or multi-band switching observations, the Macro bus can cooperate with PMAC to achieve synchronous triggering of motion control and data acquisition, effectively reducing image distortion and observation errors caused by timing deviations. This architecture not only enhances the comprehensive pointing accuracy and dynamic response speed of the telescope, but also provides solid technical support for high-resolution solar physics research. It is a representative case of the modular and real-time development of control systems in large-scale astronomical equipment.

4. CHALLENGES AND SOLUTIONS

Although bus technology plays an important role in data transmission and coordination between devices in telescope control systems, it faces several challenges, particularly in terms of bandwidth, latency, and stability, as systems become more complex and observation tasks diversify.

4.1 Challenges

In telescope systems, the amount of data generated by various devices is enormous, especially during high-resolution imaging, long-duration tracking, or large-scale data acquisition, which requires very high data transmission demands. Traditional buses may not provide sufficient bandwidth to handle these large data streams, affecting the system's response speed and data processing capability. High-precision observation tasks require strong real-time performance, especially in motion control and data feedback. Any delay will affect the accuracy of the telescope, leading to deviations in the observation results. Therefore, bus latency may become a bottleneck that impacts system performance. Telescopes typically operate in complex environmental conditions, such as high magnetic fields or significant temperature fluctuations, which can affect the stability of bus communication. Additionally, when multiple devices operate simultaneously within the system, data conflicts or transmission errors may pose risks to the system's reliability.

4.2Bus Design Optimization

To address the challenges mentioned above, the telescope control system can enhance bus design and further improve system performance and reliability through the following approaches: adopting higher bandwidth bus technologies, such as Gigabit Ethernet, to meet the large-scale data transmission demands[131-132]. Modern high-speed buses (e.g., 10Gb Ethernet) can provide higher data transfer rates, ensuring smooth data transmission and processing. Selecting low-latency bus protocols, optimizing data paths, and minimizing complex intermediate nodes. Bus protocols such as CAN and EtherCAT (via specialized real-time protocols) can maintain high reliability while reducing latency, making them suitable for systems requiring precise control and real-time feedback. Implementing redundant designs and error detection mechanisms to improve bus fault tolerance. For systems requiring high stability, dual bus architectures (e.g., dual network design) can be considered, ensuring normal operation even in the event of a bus failure. In addition, dynamic error monitoring and self-repair functions are crucial measures to enhance stability. At the bus level, a layered architecture can be employed to avoid all devices being concentrated on a single bus network, reducing conflicts and congestion. Properly planning and allocating bus bandwidth allows for prioritizing bandwidth for critical devices based on their transmission requirements. Through these optimization measures, the performance of the bus in telescope control systems can be effectively improved, ensuring the system operates efficiently and reliably under high load and high precision requirements.

5. CONCLUSIONS

In telescope control systems, bus technologies play a crucial role as intermediaries for data transmission and coordination between various devices. This review examines several common bus types, such as VME, EtherCAT, CAN, Fiber Channel and Macro, and explores their applications in telescope control systems.

The review covers the design and application of different bus types, analyzing their roles in telescopes, including pointing control, data acquisition, and real-time observation. Through efficient data transmission and coordinated control, the bus systems enable real-time communication and data sharing between subsystems, ensuring precise control and management of the telescope during observations. The choice of appropriate bus standards significantly impacts system performance, particularly in areas such as data transfer speed, reliability, and fault handling.

While current bus technologies have achieved significant success in multiple telescope projects, they still face challenges, particularly in complex observational environments with high transmission demands and time-sensitive requirements, where ensuring data accuracy and real-time transmission is critical. Additionally, as telescope functions continue to expand, higher demands are placed on the reliability, scalability, and compatibility of bus systems. Future research may focus on bus architecture optimization, the introduction of intelligent management, and improvements in adaptability for extreme observational environments. With ongoing technological advancements, telescope observation management control system buses will become more intelligent and efficient, further advancing astronomical observation technologies.

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