Avionic System Architecture Design of the Manned Deep Space Exploration Spacecraft

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Abstract. The avionic system is an important part of spacecraft, which controls and manages many functions such as telemetry and remote control, energy management, thermal control management, health management, etc. The development trend of spacecraft avionic system at home and abroad is summarized and combed. Considering the development requirements and technical characteristics of manned deep space exploration mission, an avionic system architecture of manned deep space exploration spacecraft is proposed from the aspects of network integration, computing generalization, implementation integration, software APP, etc., which provides a reference for the subsequent avionic system design.

Keywords: Manned Deep Space Exploration Spacecraft · Avionic system · Network Integration · Computing Generalization · Implementation Integration · Software APP

1 Introduction

With the continuous development of computer and chip technology, the function and performance of integrated avionic systems are continuously improved, and the application of the integrated electronic concept in spacecraft systems is more and more extensive. The spacecraft integrated avionic system covers the function of the control and management of telemetry and remote sensing, energy management, thermal control management, health management and other functions, which plays an important role in information sharing and comprehensive utilization, function integration, resource reorganization and optimization, as well as information processing and transmission [1].

The manned deep space exploration mission is complex and large in scale, with the characteristics of multiple data types, large data volume, and far data distribution. At the same time, as a manned spacecraft, it requires high reliability and security of data communication, which puts forward higher requirements for real-time performance, synchronization, interface uniformity and autonomy of avionic system response, as well as the standardization, integration, modularization, and miniaturization of electronic equipment.

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The traditional avionic system design generally adopts the “bottom-up” development mode. It is carried out according to the process of “device scheme design - subsystem selection - system integration”. Each subsystem is equipped with an independent controller and takes its own responsibility, resulting in a great waste of weight, volume and computing resources, which can no longer meet the requirements of manned deep space exploration mission. In order to optimize the resource allocation, realize the system integration and improve the system redundancy, it is urgent to establish a new development mode with unified sorting of requirements, unified allocation of resources, unified integration of functions and unified design of modules, which is called “unified avionic system”.

This paper takes network integration, computing generalization, execution integration, and software APP as the design goals, and proposes a new integrated avionic system according to the functional requirements of general computing, data exchange, acquisition drive, and astronaut support for manned deep space exploration spacecraft. This design has the advantage to optimize system configuration effectively, achieve the resource integration, and improve the system reliability.

2 Development Status of Spacecraft Avionic system

2.1 Orion Spacecraft of USA

Orion spacecraft utilizes the Time Triggered Ethernet (TTE) technology to achieve the transmission of data with different transmission reliability requirements and different data bandwidth in the spacecraft using a unified network form. High performance and high reliability general-purpose computer technology is adopted to realize the integration of the whole spacecraft control, human-computer interaction and system communication. The standard power data unit is adopted and configured nearby according to the demand to realize the distributed management of the whole spacecraft power distribution and data. The time-sharing and partition operating system is adopted to support the integration of a large number of complex software in the system and avoid the problem of system reliability reduction caused by different software operations. The independent modification and update of the software of each subsystem is supported without affecting other subsystems, which is helpful to improve the testability of the system, reduce the development and maintenance costs, and facilitate future upgrades. The avionic system architecture of Orion spacecraft is shown in Fig. 1 [2].

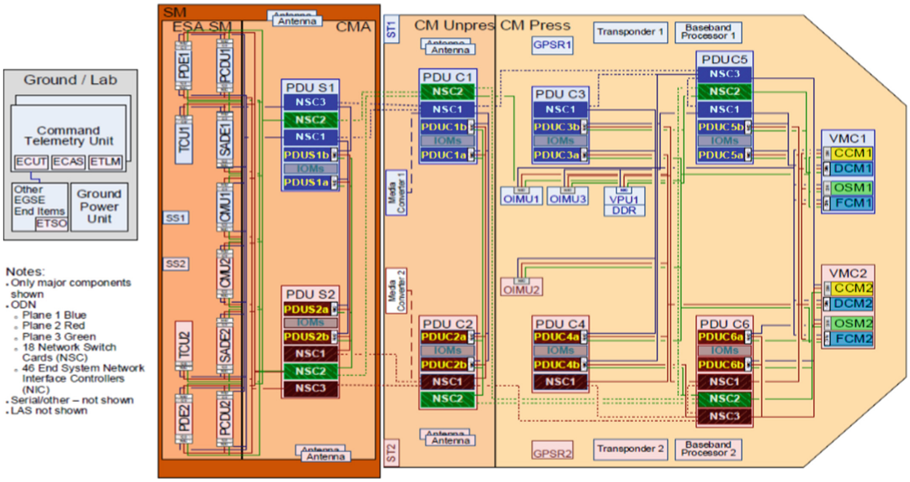

Fig. 1. The structure of avionic system in Orion spacecraft.

2.2 Ariane 6 Launch Vehicle of Europe

Ariane 6 launch vehicle adopts dual redundancy architecture, and utilizes TTE real-time bus as the backbone network communication data bus of the whole vehicle. Each level adopts modular integrated electronic equipment with the same architecture, and the equipment adopts a general backplane composed of different modular boards. The avionic system architecture of Ariane 6 launch vehicle is shown in the Fig. 2 [3].

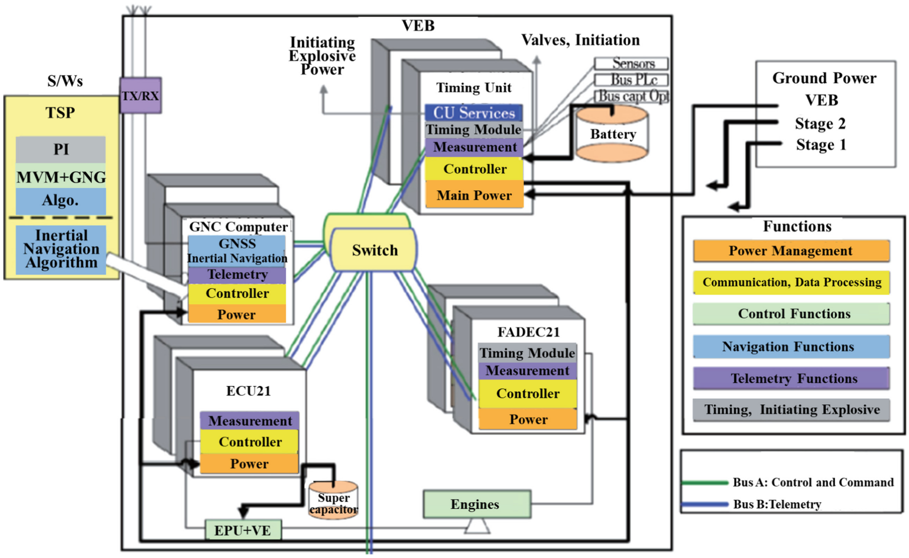

Fig. 2. The structure of avionic system in Ariane 6 launch vehicle.

2.3 Spacecraft of China

The manned spacecraft of China generally adopts the combined avionic system with the central computer as the BC of the 1553B bus, which supports the 1553B bus connection to complete the platform communication and control. The special interface is used to complete the transmission of image, voice and load data. The information system adopts a three-tier pyramid architecture. In this architecture, each subsystem is configured with an independent controller, and the acquisition and execution equipment is customized. The avionic system architecture of Chinese manned spacecraft is shown in the Fig. 3.

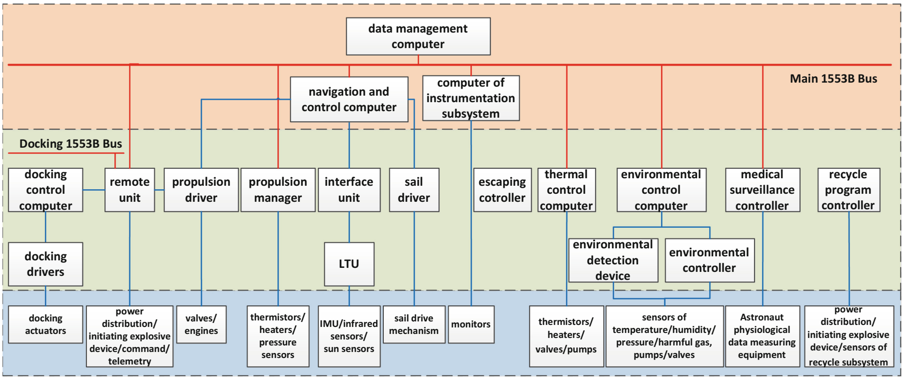

Fig. 3. The structure of avionic system in Chinese manned spacecraft.

2.4 Summary of Development Status

It can be seen that the avionic system design of Chinese manned spacecraft has some problems as follows.

a) The scalability of the combined system architecture is weak, because the subsystems are independent from each other and own exclusive resources, with little or no integration of functions;
b) The network interconnection mode composed by 1553B bus and special interface or Ethernet is complex, because there are many kinds of hard wires, serial ports, buses and networks, and the interconnection relationship is complex. Cables and connectors occupy a large amount of weight and space as well;
c) Computing capacity is insufficient, because subsystems such as data management, GNC, instrument and environmental control are equipped with dedicated computers, and computing resources are decentralized;
d) The system consists of a large number of independent device and the integration is low, because the low-level duplication is serious caused by the traditional development mode and the existing division of labor and fields of each institute;

e) Software and hardware are tightly coupled, and the development is difficult, because the scale and number of software have increased dramatically, but applications developed by different software developers cannot be seamlessly transplanted. Therefore, the further unified interfaces are needed.

In order to solve the above problems, referring to the development of the avionic system of foreign manned spacecraft, the design scheme of the avionic system of manned deep space exploration spacecraft is inspired as follows.

a) More open system architecture: adopt the top-down integrated system design to achieve a distributed, integrated, and modular system architecture;
b) More simplified and efficient network interconnection: a unified network is used to realize the integrated transmission of command and telemetry data (with high reliability and real-time requirements) and high-speed data such as image data, voice data, and payload data;
c) Faster on-board computing speed: constantly improve computer performance to meet the needs of different functions and tasks, and promote the development of spacecraft towards high intelligence and high autonomy;
d) Electronic equipment with higher integration: achieve top-level optimization and integration of electronic equipment by utilizing modular board cards to make up independent device and developing the board cards as chips.
e) Better and easy-to-use software development ecosystem: a universal software framework with hierarchical structure and time-sharing and zoning operating system are adopted to build a spacecraft software development ecosystem that supports multi-party joint and parallel development.

3 Requirements Analysis

3.1 Requirements for Higher Capacity of Independent Health Management and Task Planning

At present, China has the autonomous orbit control capability based on the target orbit and the health management capability based on the telemetry threshold. It has been successfully implemented in several tasks. The on orbit operation is normal, reducing the burden of ground personnel, improving the reliability of the whole mission, and achieving the desired results. The manned deep space exploration mission has the characteristics of greater space ground communication delay, smaller measurement and control coverage, and lower ground personnel intervention. Therefore, higher requirements are put forward for the autonomous health management and task planning capabilities of the electrical system. Common processor chips can no longer meet the task requirements, because the electrical systems need higher processing performance and computing capabilities [4].

3.2 Requirements for Higher Functional Density

According to preliminary calculation, the carrying capacity of the earth-moon transfer orbit is about 1/3 of that of the low earth orbit. Therefore, in order to complete the same function of low earth orbit spacecraft, the requirements for launch vehicles are up to three times. This requires that the manned deep space exploration spacecraft should have a higher functional density, which means that the equipment should have more functions under the condition of unit resource consumption. The key to achieve this goal is the optimal network topology and the software and hardware implementation technology of generalization, integration and modularization.

3.3 Requirements for Higher Reliability

Manned space flight is a matter of human life and can't be lost. Compared with unmanned lunar exploration missions such as Chang'e, the requirements for the reliability of the spacecraft are higher and the requirements for the redundancy design capability are stronger. In addition, because the coverage of the earth moon transfer orbit and the lunar orbit measurement and control is less, it cannot meet 100% coverage during the mission task. Once the failure occurs, there is a possibility that it cannot be handled in time, which requires the spacecraft to have higher reliability.

3.4 Requirements for Higher Capability of Attended Closed-Loop Control

Compared with machines, human intelligence has obvious advantages in target recognition, danger perception, task decision-making, etc. From the perspective of ensuring manned safety, manned deep space exploration tasks must include astronauts in the closed loop of the control system, and develop human-computer interaction technology to enable spacecraft to have higher manned closed-loop control capability.

4 Avionic System Architecture

Taking into account the technological development gap at home and abroad and the development needs of manned deep space exploration spacecraft, the avionic system design of manned deep space exploration spacecraft is mainly aimed at integration, lightweight, intelligence and convenience. The equipment integration and performance have to be greatly improved. The number, weight and volume of onboard electronic equipment should be significantly reduced, the interface has to be extremely simplified, and the cables have to be significantly reduced. Through adaptive control, autonomous fault diagnosis and fault-tolerant nursing, the autonomy, intelligence and fault adaptability of manned spacecraft during flight can be greatly improved, and the goal of upgrading and leapfrog development of avionic systems of manned spacecraft and leading the international technology direction can finally been achieved.

According to the requirements analysis, the avionic system architecture of manned deep space exploration spacecraft is proposed, as shown in Fig. 4. The avionic system of manned deep space exploration spacecraft can be divided into five functional subsystems, including general computing subsystem, data exchange subsystem, data acquisition and device drive subsystem, astronaut support subsystem and TT&C communication subsystem. The subsystems cooperates with each other to realize the functions of the integrated avionic system. The general calculation subsystem completes the numerical calculation and logic control according to the input parameters and established strategies, and outputs the calculation function of the execution results. The data exchange subsystem completes the transmission of control and measurement information between equipment in the same subsystem or different subsystems. The data acquisition and device drive subsystem completes the acquisition and drive functions of analog telemetering acquisition, temperature telemetering acquisition, sensor data acquisition, pulse command drive, power distribution control, initiating control of initiating explosive devices, heating circuit control, motor drive, valve drive, etc. The astronaut support subsystem completes voice, image, display, alarm and manual control support. The TT&C communication subsystem supports the data communication between space and ground, between different spacecraft, and supports the tracking and orbit measurement as well.

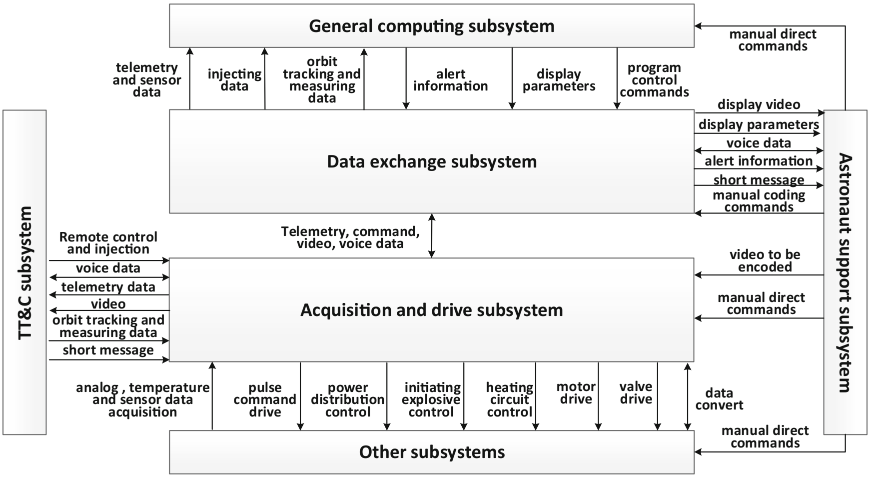

Fig. 4. The structure of avionic system in manned deep space exploration spacecraft.

The information network adopts the design idea of unified switching network. Multiple TTE network switches complete the platform control task through the connection of several general-purpose, standardized high-performance computers and modular execution service units (ESU). The three-layer hierarchical control structure of traditional manned spacecraft, which is system management - subsystem control - regional execution, is simplified into a two-layer hierarchical control structure, which is unified management - regional execution. The control hierarchy is compressed, and the probability of errors is reduced in the process of control information transmission and processing, and the system reliability is improved (Fig. 5).

High-performance computers are implemented to receive the status telemetry and sensor data transmitted by the equipment of each subsystem through the TTE network. The computers implement numerical calculation and logic control through the application strategy, and transmit the calculation results to the execution, control and display terminals through the TTE network to achieve unified closed-loop management on system level. According to the network access requirements, the TTE network switches

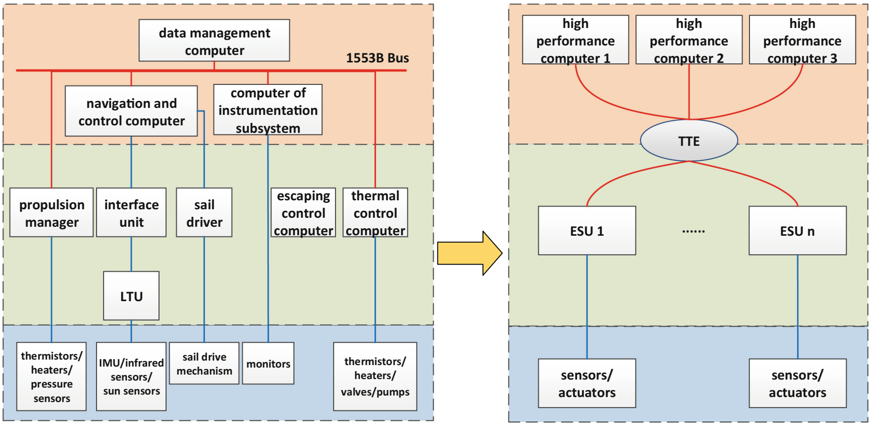

Fig. 5. The structure of hierarchy control.

are configured to interconnect with the network end node nearby. For the equipment with data exchange requirements but cannot be directly connected to the network, the system interconnection is achieved by data format conversion of the execution service units. The execution service units adopt modular design, which means that the standardized and modular function board cards are designed and then assembled according to the unified interface protocol to form execution service units with different function requirements. The execution service units are configured according to the collection and drive requirements, and provides input or output management for various sensors and actuators nearby in the layout area (Fig. 6).

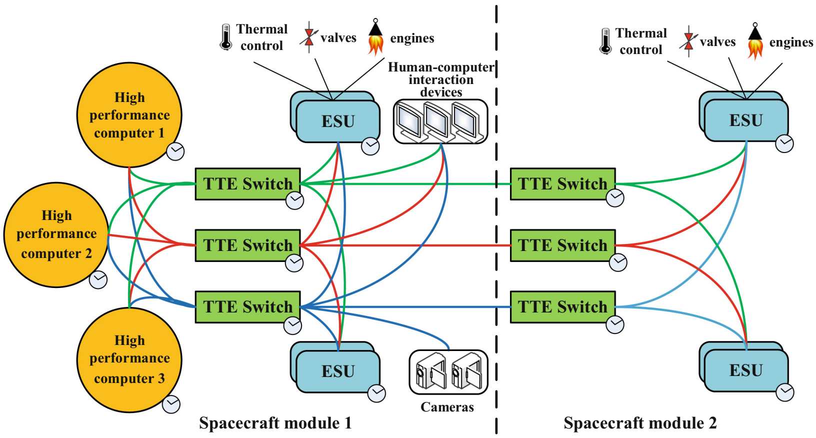

Fig. 6. The information network structure of manned deep space exploration spacecraft.

5 Key Technology Development Ideas

Aiming at the development requirements of integrated, lightweight, intelligent and convenient avionic systems, the following key technical directions will be studied.

a) Calculation generalization: high performance computers are used to upgrade the calculation ability, realize the calculation and closed-loop control functions of each subsystem, and improve the intelligence;
b) Network integration: data transmission with different real-time requirements and different service bandwidths is realized based on TTE, and integrated transmission is realized using standard protocols;
c) Implementation integration: the implement service units are modular and integrated, and different modules are configured to manage equipment nearby to achieve distributed control;
d) Software APP: the time-sharing and partition operating system is adopted to provide API and external environment interface, and to support independent compilation and dynamic loading of software APP.

5.1 Generalized Computing Technology

In order to meet the numerical calculation and logic control requirements of each subsystem and achieve the general calculation of the spacecraft, high-performance computers need to be configured. As the computing center of the spacecraft, the high-performance computer realizes computing functions of the subsystems such as data management, GNC, instrument, environmental control, thermal control, propulsion and recovery. The multi-mode redundant backup and standard modular design scheme based on high-performance processor is adopted. Internal modules are interconnected through the multi redundant high safety standard backplane bus [5], which supports the increase or decrease of module number and performance upgrade, and provides technical support for realizing system intelligence (Fig. 7).

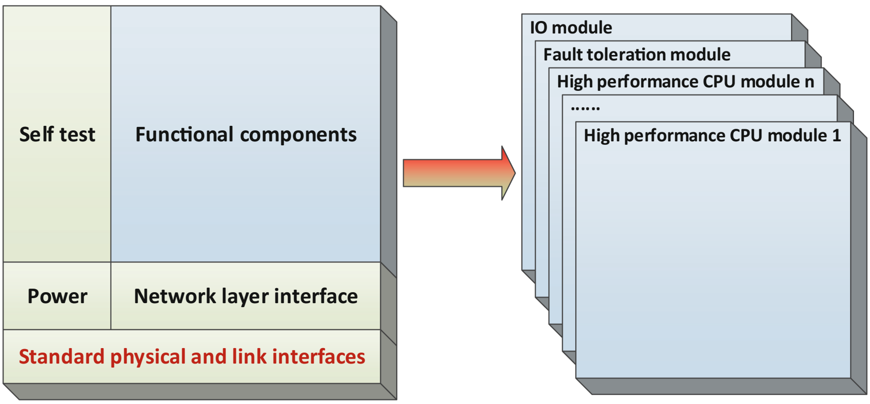

Fig. 7. The structure of high performance computer.

5.2 Integrated Network Technology

The main task of implementing data exchange through TTE is to use a unified form network to complete the reliable exchange of command, telemetry, time, sensor data, control information, image, voice, load and other data, and to support the integration of ground-spacecraft audio, video and file communication. Tasks to be completed include data management, command management, operation mode management, autonomous management, image and voice services, astronaut information services, manual operation support, etc. (Fig. 8).

Layers	Communication protocol	
Application system	ET data	TT data
Application layer	Network programming interfaces	
Transport layer	UDP	
Network layer	IP	
Data link layer	802.3 MAC protocal	TT Synchronization and service-control protocol
Physical layer	802.3 PHY	

Fig. 8. The system structure of TTE protocol.

5.3 Integrated Execution Technology

In order to meet the acquisition and driving requirements of each subsystem and realize the integration of the whole spacecraft execution, it is necessary to configure modular execution service units. As a bridge between high-performance computers and acquisition, drive and power distribution, the executive service unit realizes the system integration of telemetry acquisition, drive control and power distribution management functions of subsystems such as data management, GNC, propulsion, power distribution, recovery, thermal control, environmental control, pyrotechnics, docking mechanism, TT&C, and load. The integrated, modular and standardized board card design scheme based on ASIC technology [7] is adopted, and the configuration is carried out according to the local management principle according to the regional requirements. The execution service units are assembled through the standard backplane bus and the standard chassis, which improves the functional density of the equipment and realizes system optimization and weight reduction (Fig. 9).

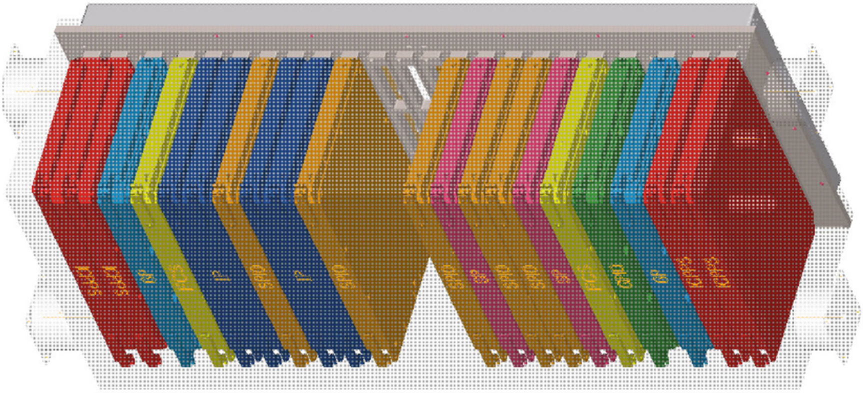

Fig. 9. The schematic diagram of ESU.

5.4 APP Based Software Technology

In order to meet the application function requirements of multiple subsystems for safe, reliable and non-interference operation on a unified computer, a time-sharing partition operating system is configured in the computer [8]. The time-sharing partition operating system enables multiple virtual partitions to run in a central processor at the same time. The running time of the partition and the storage space used are set in advance, thus the running partitions do not interfere with each other. The time-sharing partition isolation protection scheme enables software of different subsystems and different security levels to run in the same central processor, even if one partition fails, it will not affect other partitions.

The application of time-sharing and partition operating system supports the integration of a large number of complex software in the system, as well as avoiding the problem of system reliability reduction caused by the operation of different software. It also support the independent modification and update of the software for each subsystem without affecting other subsystems, which is helpful to improve the testability of the system, reduce the development and maintenance costs, and facilitate future upgrades.

6 Analysis of Technical Advantages

The avionic system of manned deep space exploration spacecraft proposed in this paper can meet the requirements of the model task, and has certain advantages in capabilities such as system fault tolerance, software definition, network transmission, system computing, acquisition and driving. These advantages are analyzed in detail as follows.

a) Enhance system fault tolerance: the configuration of multi-mode high redundancy high-performance computers, standardized distributed execution service units, and TTE networks enables the electronic devices of the whole spacecraft to have consistent functions and interfaces, providing basic technical support for the migration and reconfiguration of system tasks. With the help of the standard backplane bus with high redundancy and fault tolerance, the fault tolerance granularity of the system is reduced from a independent device to a hardware module.

b) Enhance the ability of software definition: the general hardware platform and the operating system with good compatibility and security establish the foundation for software functions definition. Load the application software APP with specific functions in the high-performance computer, and realize the software input and output support through the TTE network business planning and scheduling reconstruction, which can endow the high-performance computer with new application functions. Although the execution service unit does not use the time-sharing and partition operating system, it also has computing capacity and can use the TTE network to execute new application functions through on orbit maintenance and update of software.
c) Enhance the network integrated transmission capability: avionic system design is carried out based on the high bandwidth, high reliability and high certainty TTE network, which realizes the unified network transmission of data with different rates, different fault tolerance and different time sensitivity, simplifies the cable network of the spacecraft, reduces the number of equipment interface status, reduces the complexity of system test, and improves the spacecraft development efficiency.
d) Enhance the system computing integration capability: the computer business has been reintegrated, and hierarchical and standardized business planning has been adopted. All high-speed computing, parallel computing and closed-loop control functions are implemented in high-performance computers. The subsystems do not configure separate computers and only develop application software for independent tasks and load into independent partitions of high-performance computer operating systems to achieve system computing integration.
e) Enhance the integration capability of acquisition and drive: the concept of equipment integration is adopted to integrate the similar acquisition and drive functions of different subsystems in addition to the integrated design of the whole spacecraft's computing function. Similar functions are realized by using the same type of board cards, reducing the types of avionic device and hardware boards, and realizing the integration of acquisition and drive

7 Conclusion

Based on the analysis of development status of foreign spacecraft avionic systems, the disadvantages in China's spacecraft design, and the needs of manned deep space exploration spacecraft, this paper proposes an avionic system architecture of manned deep space exploration spacecraft. The development direction of related key technologies is put forward from the aspects of general computing, integrated network, integrated execution and software APP. Finally, the technical advantages are summarized. This architecture provides a reference for the avionic system design of manned deep space exploration spacecraft in the future.

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