Design and Implementation of Highly Integrated Electronic System for Small-Size Spacecraft

Xinfeng YAN¹, Wei LIU, Gaosi LI and Jian GENG

Beijing Institute of Space Long March Vehicle, Beijing, 10007, China

Abstract. Due to the tight installation space, strict weight requirements, numerous functional units and dense wireless equipments of small-size spacecraft, the traditional electronic system design of aircraft cannot meet the requirements of miniaturization and lightweight for small-size spacecraft. In this paper, a highly integrated electronic system suitable for small-size spacecraft is designed, in which many key technologies such as miniaturization and lightweight design technology, multi frequency wireless electromagnetic compatibility design technology, small aircraft low delay cooperative networking and high-precision differential positioning are adopted. The proposed highly integrated electronic system makes timing control, attitude and orbit control, wireless telemetry, networking communication, satellite navigation, power distribution and other functions integrated. The total weight of the system is about 7.62kg, which is much lighter than existing electronic system. The experiment results that the highly integrated electronic system achieves good effect. This technology has broad application prospects in small-size aircraft with strict weight and space requirements.

Keywords. Spacecraft, electronic system, small-size, highly integrated

1. Introduction

The electrical system on the aircraft mainly is supposed to realize various functions such as timing control, attitude and orbit control, wireless telemetry, networking communication, satellite navigation, power distribution and so on [1].

The traditional aircraft electronic system is generally composed of several subsystems such as control subsystem, telemetry subsystem, networking communication subsystem, power distribution subsystem and satellite navigation subsystem. Each subsystem is composed of several single machines. The functions of the electronic system realize through cable network interconnection within and between the subsystems. The traditional aircraft electronic system has complex equipment composition and connection relationship, large space occupation and heavy weight.

Small-size spacecraft have many features such as light weight, small size, multiple components of electronic system and complex function. The traditional electronic system design cannot meet the requirements of small space vehicle for miniaturization and lightweight.

¹ Corresponding author: Xinfeng YAN, yanxf185@163.com

Integrated electronic technology can realize the functional comprehensive design of the aircraft electronic system. Integrated electronic technology has been widely used in foreign spacecraft [2-6]. As early as the mid-1990s, the APL laboratory of American space department established the advanced satellite technology committee to study the advanced electronic system architecture for future space projects. The "Opportunity", "Courage" and "Curiosity" Rovers in the Mars exploration project adopted integrated electronic technology [7].

Domestic spacecraft such as the firefly-1 Mars probe [8], the chang'e-3 patrol [9], and the beidou-3 satellite [10] have adopted integrated electronic technology.

This paper provides an integrated electronic system design suitable for small-size spacecraft. It adopts an integrated design, has the advantages of simple electronic system equipment composition and connection relationship, small occupied space and light weight, and can meet the functional requirements of small-size spacecraft for complex electronic systems.

2. General system formula design

2.1 System composition and function

The highly integrated electronic system of spacecraft is composed of control system, telemetry system, networking communication system, satellite navigation system and power distribution system. The system composition block diagram is shown in Figure 1.

2.2 Control system

The control system mainly completes the timing control function according to the overall timing flow. According to the information from inertial measurement module, satellite navigation and star sensor, the dynamic system is controlled to work to realize

Figure 1. System composition block diagram

the attitude and orbit control function of spacecraft by solving the control equation. The control system is composed of integrated control computer, inertial measurement unit, star sensor and on-board cable network.

2.3 Telemetry system

The telemetry system receives and frames sensor image data and digital data, collects and frames analog parameters such as voltage, temperature and pressure on the aircraft, encodes the framed data by TPC, encrypts it, and then transmits the output PCM code stream with transmitter modulation and power amplification via the telemetry antenna. Due to the miniaturization design requirements of spacecraft, the functions of telemetry system such as data receiving, collecting, framing, channel coding and encryption are integrated in the control computer, which reduces the number of equipment and saves weight and size. The telemetry system is mainly composed of integrated control computer, transmitter, telemetry antenna and high-frequency cable network.

The telemetry frame format is designed as 208×64 , two subframes, each channel word length is 1 byte, the major frame sampling rate is 5.8323kHz, the subframe sampling rate is 91.1Hz, and the wireless telemetry code rate is 9.704969Mbps.

2.4 Networking communication system

The networking communication system completes the information exchange between the two spacecraft. The main interactive information includes the attitude, orbit data and satellite navigation data of the spacecraft. The networking communication system is mainly composed of networking communication components, networking transceiver antennas and high-frequency cable network.

2.5 Satellite navigation system

The satellite navigation system completes the satellite navigation and positioning of the two spacecraft, performs differential decomposition through the satellite navigation information exchanged by the networking communication system, and outputs the differential positioning results to the control system. The satellite navigation system is mainly composed of satellite navigation components, satellite navigation antennas and high-frequency cable network.

2.6 Power distribution system

The power distribution system provides 48V and 28V power supply for the highly integrated electronic system and other external systems, isolates and converts 28V, outputs one current of isolated 15V and three currents of isolated 5V voltage to other modules of the highly integrated electronic system, and completes the functions of power transfer and emergency power off. The power distribution system is mainly composed of power distribution components, control batteries and load batteries.

3. Key technologies and solutions

3.1 Miniaturization and lightweight design technology

In this paper, the miniaturization and lightweight design of highly integrated electronic system for spacecrafft is realized through the design of electronic structure integration, control computer and telemetry equipment integration, unified power supply and distribution design and so on.

3.1.1 Electronic structure integration

The power distribution components, control computer, image information processing computer, networking communication components and satellite navigation components are designed for electrical structure integration. The image information processing computer is the component equipment of load 1. The above equipments are uniformly installed in an integrated electronic cabin, and each equipment exists in the form of module components. The modules are connected through the inter board connectors. The upper and lower structure shells of integrated control computer and image information processing computer are canceled with the frame structure retained. Considering the adaptability of electromagnetic compatibility, the structure shells of power distribution components, networking communication components and satellite navigation components are also retained. In order to further reduce the weight of the equipment, the structural shell is made of magnesium lithium alloy. The schematic diagram of the integrated electronic cabin is shown in Figure 2.

Figure 2. Schematic diagram of integrated electronic cabin

X1 and X2 are inter board connector interfaces, and each component achieves power supply and data interaction through X1 and x2. The interactive signals between the integrated electronic cabin and the equipment outside are collected on the networking communication component and led out through the external interfaces IF1 and IF2. The interactive signals between the integrated electronic cabin and the ground are uniformly led out by the external interface IF3 on the control computer. The test signals of the integrated electronic cabin are uniformly led out through the test interface IF4 on the control computer.

3.1.2 Control computer and telemetry equipment integration

The traditional control computer and telemetry equipment are integrated and designed to share processing chip and interface resources. After the integrated design, the serial port circuit is reduced from 18 to 8. The functional block diagram of integrated control computer is shown in Figure 3, which is composed of main control module, interface module, power conversion module, encryption module and crystal oscillator circuit. The integrated control computer do not only realize the functions of timing control, solving control equations and controlling the power system, but also realizes the functions of data receiving, collecting, framing, channel coding and encryption of telemetry data. Among, the main control module adopts Xilinx SOC chip XC7Z020-1CLG484, together with two DDR3 chips and one nor flash chip.

Figure 3. Functional block diagram of integrated control computer

3.1.3 Unified power supply

The power supply interface of each component is integrated and designed as a power distribution component. The power distribution component is composed of power supply and distribution circuit, input EMI filter circuit, DC/DC power circuit, output filter circuit and other units. The circuit block diagram is shown in Figure 4. Among, the power supply and distribution circuit includes power transfer circuit and emergency power-off circuit, which is realized by solid-state relay. Discrete devices are used to build the input EMI filter circuit, and transient voltage suppression diodes are used to suppress the maximum 200V voltage peak of the bus. Common mode filter inductor and differential mode capacitor are selected to suppress common mode and differential mode noise. RC noise suppression circuit is adopted to suppress absorption noise. High frequency magnetic beads are used to further suppress EMI high frequency noise at the input side.

Figure 4. Circuit block diagram of power distribution component

3.2 Multi-frequency wireless electromagnetic compatibility design

The size of spacecraft is small, and the composition of wireless system on the aircraft is complex, including networking communication system, satellite navigation system and wireless telemetry system. The antennas of the three wireless systems are installed close to each other and wireless frequency points are close to each other partly. Multiple methods such as local shielding of metal shell, determination of specific frequency points through third-order intermodulation analysis, use of different antenna polarization methods to increase spatial isolation, and extra filtering of transmitting sources in sensitive frequency bands are used to jointly realize multi frequency point wireless electromagnetic compatibility in a narrow space.

3.3 Communication design of low-delay high-speed anti-interference networking

The networking communication system adopts TDMA and frequency hopping technology. Considering the minimization of transmission and processing delay, each time frame is designed to contain three time slots, as shown in Fig. 5, and each time frame is 10ms. The primary node occupies the first time slot (TS1), and the primary node has the function of network management. However, the other non-primary node occupies the second time slot (TS2). The length of time slots TS1 and TS2 is 4.5ms. In the last 1ms of each time frame (corresponding to time slot TS3), each node remains silent. The primary node senses the channel and detects the interference on each frequency point.

Figure 5. Diagram of time slot allocation

As the duration of each time slot is very short, in order to support fast reception synchronization, the system adopts several methods, such as, using Barker preamble with good correlation in the link layer, selecting MSK differential decomposition and LDPC coding to improve the transmission rate in the physical layer, and finally realizes

the effect of receiving synchronization in 0.5ms. In the physical layer, in order to reduce space loss and lower transmission power, LDPC(1536, 1024) coding is combined with MSK modulation. The bit sequence after channel coding is interleaved for MSK modulation and the receiver uses orthogonal differential demodulation. According to the antenna pattern simulation result and link calculation, within the range of $\pm 80^\circ$ antenna pattern, the bit transmission rate capability is not less than 1.33Mbps at 5km, the link margin is greater than 6dB, and the required transmission power is only 3W. Meanwhile, according to the measured results of the physical prototype, the maximum end-to-end delay of the two networking communication nodes will not exceed 14ms.

3.4 Design of high precision satellite navigation and differential positioning

The satellite navigation component is mainly composed of RF channel, navigation signal processing unit, information processing unit, interface unit, power supply unit, clock unit, etc. The composition block diagram is shown in Figure 6. The RF channel receives the GPS/B1 signal input by the antenna and outputs the IF signal to the navigation signal processing unit after amplification, mixing and filtering. The signal is captured, tracked and measured the pseudo range by the navigation signal processing unit. The information processing unit calculates the position, speed and time information of the spacecraft according to the measured pseudo range and ephemeris original information, and sends the obtained information to the control system through the interface unit.

Figure 6. Composition block diagram of satellite navigation component

In order to improve the relative position accuracy of two spacecraft, the satellite navigation differential positioning design is adopted. Each spacecraft first performs satellite receiving and positioning respectively, and then the two sides use the networking communication system to interact received the ephemeris numbers. According to the similar ephemeris numbers, the positioning results are calculated by

difference decomposition, which can offset the same position error and improve the relative position accuracy between the two spacecraft.

The error sources of differential positioning mainly include satellite clock error, satellite ephemeris, ionospheric delay error, tropospheric delay error, multipath error and receiver noise. The flight process of the spacecraft is relatively open, the number of visible satellites is more than 12 (GPS + BDS), and the PDOP value is basically less than 3. The distance between the two spacecraft is about 3km so that the included angle of the two receivers relative to the same navigation satellite is very small, and the connection between the two receivers and the navigation satellite can be considered to be parallel. After differential calculation, except multipath error and receiver noise, the positioning error caused by other error sources tends to the same side. In the positioning results, it can be considered that the relative error of the two receivers is almost equal to the positioning error of a single receiver. According to the calculation, the relative error of the dual receiver is not more than 15m.

3.5 Centralized data interaction and management architecture based on integrated control computer

The integrated control computer is the general controller of the spacecraft, which is used to collect the information of inertial measurement unit, image information processing computer, satellite navigation component and star sensor, control the power system, load, networking communication component and other equipment according to the control equation and control sequence. The integrated control computer is also used to communicate with the rocket and the ground test bench and make the two spacecraft perform the corresponding sequential actions. The communication interface between devices is the byte-by-byte transmission interface, such as isolated RS422 or RS485. The communication connection relationship between devices is shown in Figure 7.

Figure 7. Communication connection relationship between devices

The data frame format consists of frame header, command byte, data, fill byte, check code, data length and frame tail, as shown in Table 1.

Table 1. Definition of data frame format

Order	1	2	3	4	5	6	7
Field	Frame header	Command byte	Data	Fill byte	Check code	Data length	Frame tail
Number of bytes	2	1	Floating length (0 ~ 249)	1	1	1	2

In order to improve the reliability of data interaction, redundancy design is adopted. For the instruction with response, if no reply is received within 200ms after the instruction is sent, the instruction will be retransmitted, and the above process can be repeated twice. As long as the correct reply is received, the process will be stopped. If no reply is received for three times, the function of the instruction is considered failed.

For the instruction without response, the send will be stopped after three times continuously at an interval of 10ms. If the receiver captures the correct instruction once, it will respond to the instruction.

4. Experiment results

The highly integrated electronic system is applied to a spacecraft. After a number of test assessments and the flight test successfully completed with a project, the system works as expected and achieves good results, which verifies the correctness and matching of the design of the highly integrated electronic system. The total weight of the highly integrated electronic system is 7.62kg, and, however, the weight of existing electronic system is normally more than 15kg because of the independent design of functional modules. In terms of power consumption, the overall power consumption of the highly integrated electronic system is about 160W. In contrast, the overall power consumption of the existing electronic system is about 280W.

The telemetry subsystem in the highly integrated electronic system obtains complete telemetry data such as image, control and analog data. The data are detected, stripped, subcontracted and processed. The analysis results show that the working sequence of the spacecraft is correct, the flight attitude and orbit control works well, the networking interaction between the two spacecraft is fluent, and the satellite receiving and positioning and differential resolution works as expected. The temperature curve of a test is shown in Figure 8, the distance curve of two spacecraft is shown in Figure 9, and the change curve of spacecraft PDOP value is shown in Figure 10.

Figure 8. Temperature curve of a test

Figure 9. Distance curve of two spacecraft

Figure 10. Change curve of spacecraft PDOP value

5. Conclusion

This paper introduces a highly integrated electronic system suitable for small-size spacecraft. Under the constraints of tight installation space, strict weight requirements, numerous functional units and dense wireless equipment, it realizes the integration of timing sequence, attitude and orbit control, wireless telemetry, networking communication, satellite navigation, power distribution and other functions. The miniaturized highly integrated electronic system breaks through the key technologies such as miniaturization and lightweight design, multi-frequency wireless electromagnetic compatibility design, small aircraft low-delay cooperative networking and high-precision differential positioning. The experiment results that the highly integrated electronic system achieves good effect. This technology has broad application prospects in small-size aircraft with strict weight and space requirements.

Reference

- [1] CHEN Shimiao1, NI Shuyan, LIAO Yurong. Summary of Integrated Electronic Systems of Microsatellite [J]. SPACE ELECTRONIC TECHNOLOGY, 2020,5:82-87.
- [2] BLUE R C, BOLOTIN G S, Development of a new generation of avionics for space applications[C], X2000 Advanced Avionics Project. Citeseer, 2003:1-5.
- [3] Nguyen Q, Yuknis W, Pursley S, et al. A high performance command and data handling system for NASA's lunar reconnaissance orbiter. AIAA Space 2008 Conferece & Exposition, San Diego, California, 2008. 1-8.
- [4] Berger R, Burcin L, Hutcheson D, et al. The RAD6000MCTM system-on-chip microcontroller for spacecraft avionics and instrument control. Proceedings of IEEE Aerospace Conference, 2008. 1-14.
- [5] Rufino J, Craveiro J, Verissimo P. Building a time-and space-partitioned architecture for the next generation of space vehicle avionics. IFIP International Federation for Information Processing, 2010. 179-190.
- [6] ZHAI J Q, Li X F, Introduction of oneWeb system and domestic LEO internet satellite system[J]. Space Electronic Technology ,2017, 14(6):1-7.
- [7] Bajracharya M, Maimone M W, Helmick D. Autonomy for Mars rovers: Past, present, and future. IEEE Computer Society, 2008. 44–50.
- [8] GAI Jian-ning, FAN You-cheng, SHEN Li, et al. Design of Integrated Electronic Subsystem of YH-1 Mars Probe[J]. AEROSPACE SHANGHAI, 2013,30(4):139-146.
- [9] Chen J X, Zhang Z, Wang L, et al. Design and realization of the integrated electronic system for the Chang'E 3 lunar rover (in Chinese). Sci Sin Tech,2014, 44: 450–460.
- [10] Jia W S, Zeng L L, Li L M, et al. Design of Beidou-3 satellite avionics system[J]. Astronautical Systems Engineering Technology,2020,4(6):50-55.