Visual Image Downtransmission of Landing Phase for Deep Space Explorers

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Abstract. Visual image transmission during power descent or landing segment is needed in deep space probes, while the bandwidth of transmission channel is limited and the information transmission rate is low in deep space communication. In view of this contradiction, a rate-adaptive visual image transmission scheme is designed in this paper. Key problems such as frame extraction and playback, frame format identification, joint scheduling are solved. Visual transmission of image under the condition of limited communication rate is realized by the scheme, with the characteristics of real-time performance, rate adaptation, image integrity, etc. At the same time, the concrete implementation and experimental verification of the scheme in engineering are given, which provide reference for the design on spacecraft data management system.

Keywords: Deep space communication · Power descent · Rate adaptation

1 Introduction

The landing camera mounted on deep space probe is installed at the bottom of the lander and perpendicular to the lunar surface. It is used to acquire the image data of the lunar surface in the dynamic descending phase of the probe in real time. The frame rate of the image is not less than 10 frames/s and the peak image transmission rate is higher than 10 Mbps [1]. In order to visualize the landing process of the probe, it is necessary to download the latest image generated by the landing camera as soon as possible. Deep space communication has the characteristics of long communication distance and serious signal attenuation. At the same time, the antenna gain and transmission power of deep space spacecraft are limited, and the signal reaching the ground station is very weak [2]. Therefore, in order to ensure the reliability of long-distance data transmission, the deep space communication rate is generally not too high [3]. At present, the deep space data transmission to ground communication rate is generally below 2 Mbps. Telemetry data, detection data and image data generated by the lander are transmitted to the ground by the relay star after unified routing and coding. The available communication rate for image data does not exceed 500 kbps. In this case, there is a contradiction between the image generation rate and the downlink rate. Therefore, it is necessary to design a

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visual image transmission scheme. At the same time, deep space probe is a system with limited resources, so the complexity of project engineering should be reduced as much as possible.

A multiplex memory is designed in the data management subsystem of deep space probe, which is responsible for the joint scheduling, storage and down-transmission of the probe data, image data and telemetry data of the whole device. According to the demand for data transmission in different application scenarios, multiplex memory can realize flexible data flow management. In the power descent section, the storage and transmission requirements of image data are: (1) All the data generated in the power descent section need to be stored in the mass storage. When the detector reaches the lunar surface and the communication channel to the earth is available, the stored data can be selectively played back and transmitted down. (2) During the landing of the probe, the latest image generated by the landing camera is transmitted in real time. There are several schemes to realize visual download of images in the multiplex memory:

Scheme 1: The image data of the landing camera are simultaneously input to the storage channel and the downlink channel. In the data stream design of the memory channel, since the programming rate of the memory chip is higher than the peak input rate of the image, it is not necessary to distinguish the content of the image and can be stored directly by bit stream [4]. However, in the data stream design of the downlink channel, in order to ensure the integrity of the downlink image, the whole image needs to be buffered, then whether the downlink channel is idle or not is judged, and when the channel is idle, data is read from the buffer for downlink. The advantage of this scheme is that it is simple to implement and compatible with the overall data flow of the multiplex memory. Disadvantages are: (1) Due to the need to cache a complete image, when the image is large, the cost of the required hardware resources increases; (2) After an image cache is full, it starts to read the download, which has poor real-time performance.

Scheme 2: The image data of the landing camera is input into the storage channel. The playback mode can be selected as playback by time or playback by address [4, 5]. The above two playback modes require the ground to obtain the storage time or address of the latest image of the landing camera in advance, and inject playback instructions including the playback time or address into the detector. The disadvantages of this scheme are: (1) The application is complicated, which is not conducive to the realization of autonomous storage and playback management; (2) The storage time or address of the latest image can only be accurately estimated on the premise that the input rate of the image is unchanged, and the visual transmission with adaptive rate cannot be realized.

Scheme 3: The image data of the landing camera is stored and transmitted down in the way of recording while playing. At the same time, a special playback mode is designed. In this mode, images are marked with special marks while being stored. During playback, the latest images with special marks are read and downloaded by frame drawing playback [6]. This scheme is compatible with the design state of the lander's multiplex memory, and only one additional information register and a set of latest image storage address registers need to be added to the hardware overhead. This paper focuses on the overall design and key technologies of the scheme.

2 Overall Scheme Design

The landing camera is connected to the multiplex memory through LVDS (Low-Voltage Differential Signaling) interface, and the data content includes high compression ratio image data and low compression ratio image data. The two kinds of data appear at intervals of one picture, and the transmission ratio is variable. The default is 64:1, that is, 64 of 65 images are of low compression ratio and 1 is of high compression ratio.

In order to realize the visual transmission of the image of the landing camera, it is necessary to store all the image data and transmit the high compression ratio image in real time. Considering the design overhead of detector hardware and software resources, the processing of landing camera images should be compatible with the overall design of the multiplex memory. Figure 1 is a design block diagram of a multiplex memory. On this basis, the scheme for realizing the visual transmission of the image of the landing camera is as follows:

(1) The image data sent by the landing camera to the multiplex memory first passes through the image format identification and framing module to separate, segment and distribute the virtual channel identification between the high compression ratio image and the low compression ratio image.
(2) Each high compression ratio image is organized and defined by the Consultative Committee for Space Data System (CCSDS) as an Advanced Orbiting System. AOS) frame format carries out Virtual Channel Data Unit (VCDU) framing on image data, including 1 frame header VCDU, 1 frame tail VCDU and several frame middle VCDU.
(3) The storage combination module performs combination scheduling on the high compression ratio image VCDU and VCDU generated by other loads, and stores the VCDU into a storage carrier after competing for a storage channel.
(4) The playback control module in the storage carrier uses a frame extraction playback method in the power down section to play back the VCDU frame of the high compression ratio image from the storage carrier. The specific work flow is as follows: 1) The storage carrier loads the storage address of the latest image and plays back sequentially from this address; 2) When playing back to the end of a high compression ratio image, completing frame drawing playback of an image; 3) Repeat the above steps to extract and play back the next image.
(5) The screened and filtered high compression ratio image VCDU frame and other real-time downlink frames are sent to the data transmission transponder after downlink combining and encoding.

According to the above processing flow, the key technologies involved in this scheme include frame extraction and playback algorithm, frame format identification method, combined scheduling algorithm, etc.

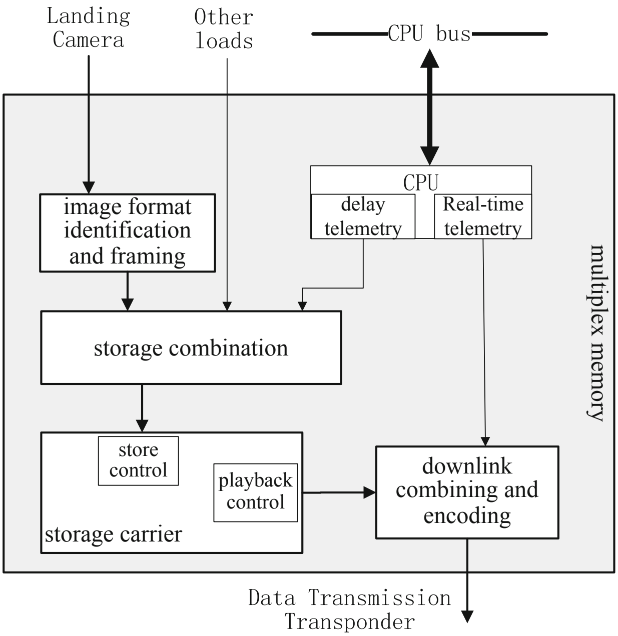

Fig. 1. Design block diagram of a multiplex memory

3 Key Technologies

3.1 Frame Extraction and Playback Algorithm

The frame extraction and playback algorithm is mainly implemented in two modules: storage control and playback control. Figure 2 is the principle block diagram of the frame extraction and playback algorithm. In order to accurately identify a complete high compression ratio image, the data frame after AOS framing needs to design additional information to distinguish VCDU header frame, VCDU tail frame and VCDU intermediate frame of the high compression ratio image, and the additional information needs to be saved at the same time during storage.

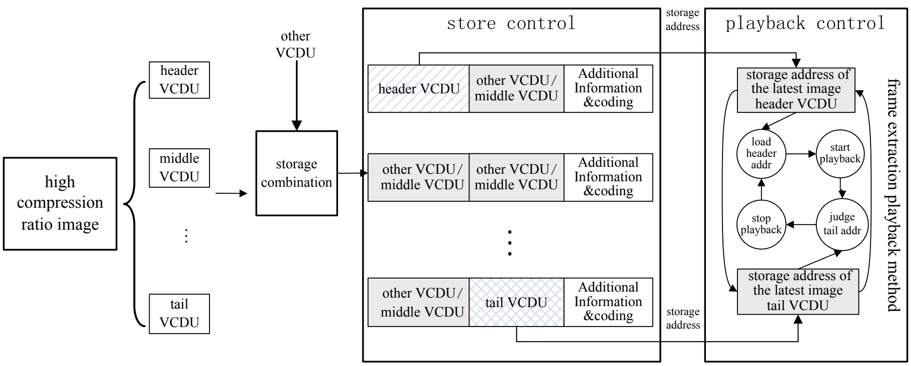

Fig. 2. The block diagram of the frame extraction and playback algorithm

The multiplex memory uses NandFlash as the storage carrier; each page is 2 KB in size and can store two VCDU frames. When storing by page, in addition to the data content of VCDU frame, additional information and coding check bits need to be saved. Because NandFlash is access by a combined schedule mechanism, data stored on that same page may include different VCDU frames generated by various load. Additional information needs to distinguish the data content stored in NandFlash pages. The format design of additional information is shown in Table 1.

Table 1. Format of additional format

Bit	B1:B0	B2:B3	B4:B5
Definition	Number of high compression ratio image frames in this page	Content of the 1st frame	Content of the 2nd frame
Meaning of each state	00: 0 frame	00: header VCDU	00: header VCDU
	01: 1 frame, the 1st frame in this page	01: middle VCDU	01: middle VCDU
	10: 1 frame, the 2nd frame in this page	10: tail VCDU	10: tail VCDU
	11: 2 frames	11: invalid	11: invalid

The playback control module needs to be set to the frame extraction playback mode in the power down section. This mode is different from the traditional sequential playback or site selection playback. It is a playback mode that can run autonomously. Through the autonomous management of playback address loading, playback start and playback stop, the extraction and download of high compression ratio image frames is realized. When the next row number transmission channel is available, the playback control module loads the latest image header frame storage address and sequentially plays back from the address. In the playback process, the additional information stored in the page NandFlash is first read, VCDU frames of non-high compression ratio images are filtered out according to the content of the additional information, and only VCDU frames of high compression ratio images are transmitted to the downlink combining module. When the playback address is equal to the latest image tail frame storage address, playback is stopped. After that, the image header storage address is reloaded. If it is consistent with the previous header address, it is considered that there is currently no new image storage. The playback module continues to wait in the stopped state, and starts a new round of extraction playback flow when the newly loaded header frame address changes.

3.2 Frame Format Identification Method

In the image format identification and framing module, two kinds of image data of the landing camera are distinguished. 1) LVDS signals are converted into byte signals through serial-to-parallel conversion; 2) Sliding matching byte signals; 3) After the frame headers are matched, starting statistics on the length and number of subsequent data blocks; 4) When the length and number of data blocks are consistent with the frame structure shown in Fig. 1, buffer and frame the data, otherwise re-detect the frame header. The two receiving modules adopt exactly the same processing structure, except that the data block length and the numbers of data blocks are designed differently. In the process of FPGA engineering, it can be realized by instantiating two identical modules and setting different parameters.

3.3 Combination Scheduling Algorithm

This scheme involves the combination of two parts: 1) All load (including landing camera) data need to go through unified combination scheduling before storage; 2) Joint dispatching of telemetry data, playback data and other real-time data before downlink. When designing multiple virtual channels, reasonable scheduling algorithm and priority control strategy should be adopted to ensure the data rate matching before and after the channel combination and improve the transmission efficiency. CCSDS recommends a combination scheduling algorithm including [7] fixed priority scheduling algorithm, polling priority scheduling algorithm, residual priority scheduling algorithm, etc. The advantages and disadvantages of the above algorithms are different in different application scenarios and scheduling requirements. This paper designs a priority scheduling algorithm based on working mode according to the storage and downlink requirements of the detector in power descending section, visible arc section and invisible arc section. Different scheduling mechanisms are adopted in different modes, and a combination of fixed priority and polling priority is adopted. The specific design is shown in Table 2.

Table 2. Priority scheduling strategies for different operating modes

Operating mode	Storage priority	Downlink priority
Power decent segment	Fixed priority: 1. Landing camera data 2. Delay telemetry 3. other load data	Fixed priority: 1. Playback data 2. Real-time telemetry 3. other real-time data
Visible segment	Polling priority	Fixed priority: 1. Real-time telemetry 2. Playback data 3. other real-time data
Invisible segment	Polling priority	Downlink prohibition

4 Performance Analysis

4.1 Downlink Real-Time Analysis

The frame extraction and playback algorithm adopted in this scheme updates the storage addresses of the head frame and the tail frame of the image after receiving a complete high compression ratio image data. Considering the worst case, when the latest high compression ratio image is received, the frame extraction playback of the previous image has just started, and the processing delay at this time is the sum of the image receiving time and the input time interval of the two images. The LVDS interface rate of the landing camera is R_{up}, and the frame length of high compression ratio image is L_{imag}, then the receiving time of a high compression ratio image is

$$T_{recv} = L_{imag}/R_{up}$$

The imaging frequency of the landing camera is N frames/s, the interval between two high compression ratio images is K frames, and the time interval is about

$$T_{int} = K/N$$

In the worst case, the processing delay of the image is

$$T_{delay} = T_{recv} + T_{int} = L_{imag}/R + K/N$$

After the download of the n^{th} image is completed, the storage address of the latest image is the storage address of the $(n + 2)^{nd}$ image. After the address is updated, the data content of the $(n + 2)^{nd}$ image is returned and the processing delay is automatically adjusted to T_{recv}. The delay of subsequent image processing is kept at T_{recv}, which meets the requirement of visual transmission.

4.2 Downlink Integrity Analysis

The integrity of image download refers to the complete download of M VCDU frames of a high compression ratio image, and the transmission process is not affected by other events. In the frame-drawing playback mode, the four states of the playback control state machine operate autonomously. The two registers of the head frame storage address and the tail frame storage address of the latest image are refreshed simultaneously only in the stop playback state and not in other states. This processing mechanism can avoid the incompleteness of the downlink image caused by the asynchronous update of the head frame storage address and the tail frame storage address.

4.3 Adaptive Analysis of Downlink Rate

The rate adaptation of this scheme includes two aspects, one is the input rate adaptation of high compression ratio image data, and the other is the downstream rate adaptation of data transmission. The input rate affects the storage efficiency of NandFlash, while the downlink rate affects the reading efficiency of NandFlash. The two rates are decoupled through NandFlash chips. When the high compression ratio image data input rate exceeds the data transmission downlink rate, the storage addresses of the head frame and tail frame of the latest image will cover the storage addresses of the head frame and tail frame of the previous image, so as to ensure that the content of the downlink data is newly generated. Through this way of address real-time coverage, the scheme is not affected by the input rate of image data and the downlink rate of data transmission, and the actual downlink image is the whole image after adaptive extraction.

Set the downlink rate as R_{down}, the downlink VCDU frame length as L_{VCDU}, and the time required to transmit a high compression ratio image is

$$T_{down} = L_{VCDU} * M/R_{down}$$

When R_{down} is 50 kbps and 280 kbps, the time required to download a high compression ratio image is 6.226 s and 1.118 s respectively. When the imaging frequency of the landing camera N is 10 frames/s and the transmission ratios of high compression ratio images and low compression ratio images are 1:8, 1:16, 1:32 and 1:64 respectively, the sequence numbers of images received on the ground are shown in the following table. Under several ratios, the input frequencies of high compression ratio images are 0.8 s/image, 1.6 s/image, 3.2 s/image and 6.4 s/image respectively. As can be seen from Table 3, when the data transmission downlink rate is greater than the image input rate, all high compression ratio images can be transmitted without interval. When the downlink rate of data transmission is less than the input rate of images, the serial numbers of the downloaded images are discontinuous, there is a certain interval between the serial numbers of the two images, and the downloaded images are the latest generated data content.

Table 3. High compression ratio image sequence number under different input ratio and downtransfer rate

Proportion	Image sequence number at downlink rate of 50 kbps	Image sequence number at downlink rate of 280 kbps
1:8	1, 9, 17, 25, 32, 40, 48	1, 2, 3, 4, 5, 6, 7
1:16	1, 5, 9, 13, 17, 20, 25	1, 2, 3, 4, 5, 6, 7
1:32	1, 3, 5, 7, 8, 10, 12	1, 2, 3, 4, 5, 6, 7
1:64	1, 2, 3, 4, 5, 6, 7	1, 2, 3, 4, 5, 6, 7

5 Engineering Implementation and on-Orbit Verification

At present, the scheme has been implemented on FPGA, and the chip model is Xilinx aerospace chip XQR2V3000. The multiplex memory, as an important module of Chang 'e–4 data management subsystem, has been verified on-orbit. On the morning of January 3, 2019, Chang 'e–4 probe began to land, the multiplex memory was set to the frame-drawing playback mode, and the downlink rate was set to 50 kbps. After the landing camera was turned on, the high compression ratio image began to be automatically downloaded and updated about 6.4 s, which successfully realized the visualization of the landing process. Figure 3 is a real shot high compression ratio image transmitted down from the power down section. The on-orbit operation state of Chang 'e–4 shows that under the condition of limited data transmission communication rate, the visual transmission of images in the power descent stage is realized, and the equipment works stably and normally.

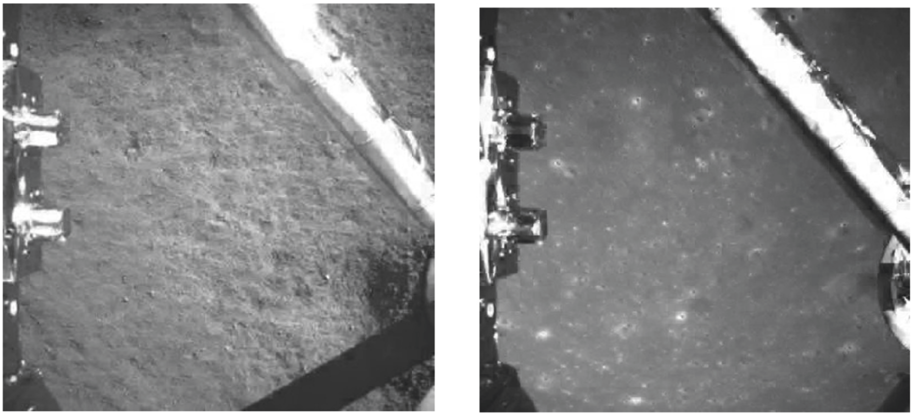

Fig. 3. Downward image of Chang'e–4 probe during power descent

6 Conclusions

This paper designs and implements a visual image transmission scheme with adaptive rate of dynamic descending segment. The scheme recognizes the latest image frame by setting the frame extraction playback mode for extraction playback and downloading. Under the condition of limited data transmission communication rate, it realizes the storage management and visual downloading of the image of the descending camera. It has the characteristics of high real-time, rate adaptation and image integrity.

In the image visualization transmission scheme proposed in this paper, it is required that the low compression ratio image and the high compression ratio image of the landing camera can be distinguished in data format. The following research focuses on designing a general image visualization transmission scheme without limiting the data format of the load image. At the same time, the robustness and scalability of the scheme are further improved, which provides a reference for the design of spacecraft on-board data management subsystem.

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