



A Novel Protocol and Layered Implementation for Spacecraft Telecommand and Device Management

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Abstract. The application of CCSDS telecommand space data link protocol in the Chinese space field is still limited to intra-spacecraft communication recently, and the research on the standardized protocols and layered system architecture which is suitable for inter-spacecraft telecommand data forwarding is still insufficient. In this paper, we introduce a new protocol based on telecommand space data link protocol and a novel layered implementation of the protocol, which enables interpreting and forwarding uplink data, device management command and manual control command through unified protocols, processes and modules. Comparing to traditional protocol and implementation of spacecraft telecommand, the new protocol and corresponding implementation has great advantage in terms of standardization, flexibility and extensibility, and has been applied to a large spacecraft assembly.

Keywords: Protocol · Layered implementation · Telecommand · Device management

1 Introduction

With the emergence and development of various complex space missions, such as spacecraft rendezvous and docking [1, 2], more collaborative controls and data interactions between different types of spacecrafts and between devices within spacecraft are needed. Besides, the standardization of the inter-spacecraft and intra-spacecraft information exchanging interface is expected to be enhanced constantly. To meet above requirements, it is necessary to adopt standard protocols for command and data interaction within spacecraft data management system and design the system architecture for information interaction in modular, scalable and flexible way. At present, there are some applications of telecommand space data link protocol in the Chinese space field [3–8], but the research on modularized and layered system architecture design and implementation is still insufficient. In this paper, we propose a unified protocol and corresponding layered implementation for spacecraft telecommand and device management, which standardizes inter-spacecraft and inter-device interfaces. In the implementation, the telecommand space data link protocol are strictly followed, the interfaces between

layers are clearly defined, and each layer can be independently expanded to meet the requirements for various types of collaborative controlling, information interaction, and system rebuilding in the large orbiting spacecrafts.

2 Unified Design for Telecommand and Device Management

2.1 Design

The data management system (DMS) in large-scale spacecraft assembly needs to process and forward commands from different sources. Typically, there are two types of commands:

1. uplink telecommands from N ($N \geq 2$) physical channels which are from different telecommand systems.
2. manual commands and device-to-device commands from M ($M \geq 3$) member spacecrafts in the spacecraft assembly.

The process of forwarding command includes multiple steps:

1. collecting command from bus.
2. storing, verifying and parsing data.
3. addressing and routing.
4. packing and delivering message.

In traditional design, for each source S , there is a unique data processor (DP) to forward commands from S . Assume the average complexity of DP is C_0 , let C_1 denote the complexity of DMS in single spacecraft and let C_{all} denote the complexity of DMS in the whole spacecraft assembly. It is easy to know that

$$C_1 = (M + N) * C_0$$

$$C_{\text{all}} = M * C_1 = M * (M + N) * C_0$$

So C_{all} increases quadratically with M , which is the number of member spacecraft. Besides, each time when a new member spacecraft join the spacecraft assembly, the DMS in original M member spacecrafts are all required to be upgraded to support the new member spacecraft. Obviously, the design is not scalable and extensible, and is not suitable for DMS in large-scale spacecraft assembly.

The key problem in the traditional design is that the data structures used in different channels and sources are different, and thus make the DP not sharable. Be inspired by the observation, in following sections, we proposed a new design of DMS which can unify the data structures and make DP sharable, so that the complexity of DMS in the whole spacecraft assembly will not increase with the number of member spacecrafts. At the same time, the extensibility and scalability of DMS is improved significantly because the DMS in all existing member spacecrafts does not need to be upgraded when a new member spacecraft joins the spacecraft assembly.

There are some key challenges in the new design, for example,

1. There are 1 USB channel and several relay channels in a large-scale spacecraft assembly, and each channel has its own telecommand system. The length of telecommand frame, transmit rate and format of frame of each channel are significantly different. To ensure the DP for telecommand can be unified, the new design of data structure for telecommands must be adaptive to the characteristics of different physical channels. So, in this paper, we propose a new data structure for uplink telecommand that can improve the utilization of channel bandwidth and simplify system design:
 - a. The telecommand frame of different channels is filled with variable-length transfer frames which share the same format.
 - b. The variable-length transfer frames adapt to variable transmit rate of different channels.

2. Device-to-device command is the command sent actively from any device in assembly to other devices. Manual command is the command sent actively from astronaut to devices. In traditional design of DMS, those commands are often implemented as customized simple command in private format, which can't be addressed in larger scope and thus can't meet the needs of forwarding command multiple times among multiple spacecrafts. In this paper, we propose a new way of defining and implementing device management command that can support transferring any device-to-device command and manual command on the bus network in assembly:
 - a. The structure of data frame is the same as telecommand transfer frame except the length of frames are different. So that the telecommand and device management command can be processed and forwarded in a unified way.
 - b. To improve the utilization of system resource and reduce the overhead of bus, the length of frame for device management command is only the length of command data packet plus the length of frame primary header.

In following sections, we will introduce the new design in detail.

2.2 Data Structure for Uplink Telecommand

Referring to the standard of telecommand space data link protocol, a transfer frame consists of frame primary header, frame data field and frame error control field, as depicted in Fig. 1. The frame data field contains one or more telecommand packets, which consists of packet primary header, packet secondary header, application data and packet error control field.

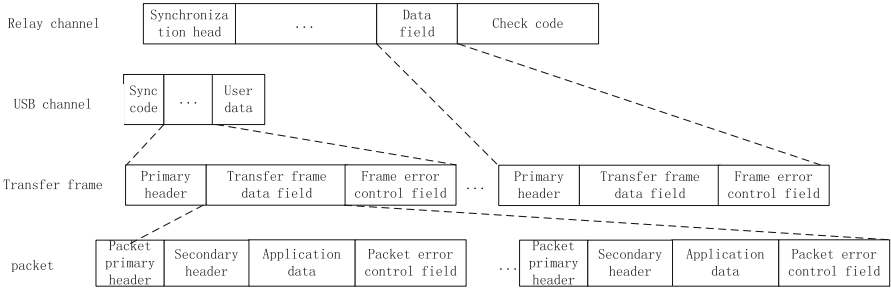


Fig. 1. Data structure of uplink telecommand

Several identifiers are put in the data structure to support command processing and forwarding. In the frame primary header, there are spacecraft identifier, which is used for distinguishing different spacecrafts, and virtual channel identifier (VCID), which is used for distinguishing different users in one spacecraft. In the packet primary header, there is application process identifier (APID) that is used for identifying a unique device.

Based on the layered data structure defined above, DMS can forward user data from different source and to different destination transparently, and thus significantly enhance the flexibility and scalability.

2.3 Data Structure for Device Management Command

To unify the process of uplink telecommand and device management command (DMC), we use the same data structure to represent DMC. As depicted in Fig. 2, the frame data field of DMC contains a command source packet and padding zeros, which are used for ensuring the size of transfer frame can reach the lower limit of size of transfer frame. The command source packet follows the same data structure as the telecommand packet.

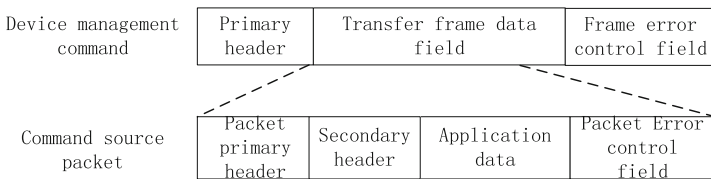


Fig. 2. Format of the device management command

2.4 Layered DMS Implementation Mechanism

Based on the data structure for uplink telecommand and DMC described in Sects. 2.2 and 2.3, in this paper, we propose a layered DMS implementation mechanism to simplify and unify the process of executing and forwarding uplink telecommand, device management command and manual command.

Figure 3 depicts the layers defined in DMS and how data flow passes layers. There are four layers in DMS: application layer, transport layer, network layer and data link layer, including data link protocol sublayer and sync. And channel coding sublayer. The design of interface between layers has referenced the Space Communications Protocols of CCSDS.

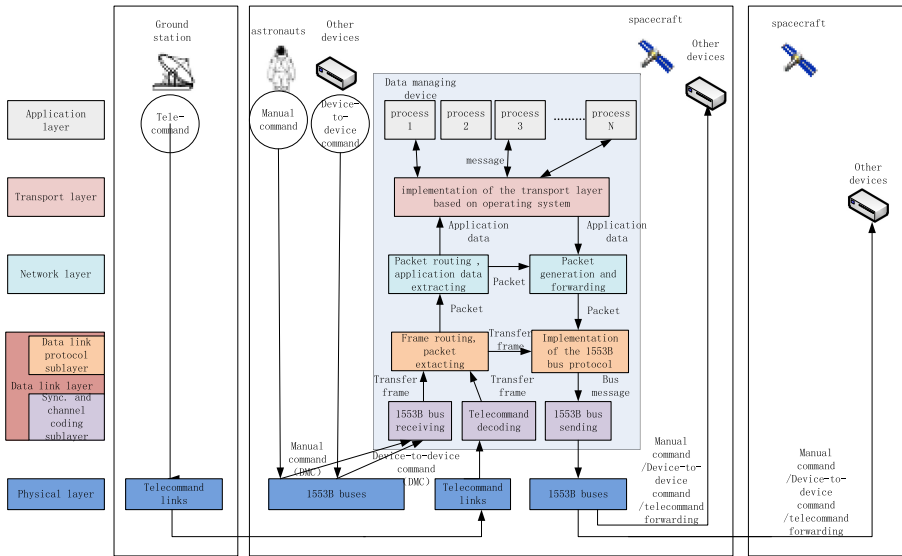


Fig. 3. Layered DMS implementation

The key functionalities of each layer are:

1. The sync. And channel coding sublayer shields the difference between physical layers, hides the details of encoding and decoding data from the different data sources, extracts transfer frames which have the same format, and thus allow subsequent layers to exchange data through unified data interface.
2. The data link protocol sublayer has three major functions:
 - a. Routing transfer frames to proper destination base on destination ID stored in the transfer frame.
 - b. Extracting packets from input transfer frame and sending to the network layer for processing.
 - c. Implementation of the 1553B bus protocol.
3. The network layer has following major functions:
 - a. Routing packets to proper destination based on destination ID stored in the packet.

- b. Extracting application data from input packet and sending to the transport layer.
 - c. Generating packets and forwarding them to the data link layer.
4. The transport layer leverages the messaging mechanism provided by operating system to distribute application data to proper process and allows inter-process data exchanging.
 5. The application layer consists of multiple application processes. It performs concrete data managing functions, such as telecommand, telemetry, program controlling, manual controlling, autonomous management, etc.

Taking a data managing device which adopts the new mechanism as example, the detailed process of parsing and forwarding data is:

1. Parsing process
 - a. Data and commands from different uplink channels and from on-board data buses are processed by the sync. And channel coding sublayer, and the complete transfer frame is extracted accordingly.
 - b. After received transfer frame, the data link protocol sublayer checks the spacecraft ID in the transfer frame.
 - (1) If it is not the native spacecraft ID, the entire frame is forwarded directly to corresponding spacecraft for disposal.
 - (2) Otherwise, the VCID in the transfer frame header is identified.
 - i. If it is not the virtual channel frame that should be processed by this device, the entire frame is also forward directly to the remote terminal (RT) address corresponding to the VCID through the bus.
 - ii. Otherwise, the integrity of frame is verified. The frame is dropped if verification fails. Otherwise, packets are extracted from the transfer frame and sent to the network layer.
 - c. For each packet, the network layer checks the APID in the packet primary header.
 - (1) If it is not the command that should be executed by the device, the entire packet is sent to the RT address corresponding to the APID through the bus.
 - (2) Otherwise, the application data are extracted from the packet and sent to the transport layer.
 - d. Based on the type of application data, the transport layer packs the application data into messages and distributes messages to proper processes in the application layer.
 - e. The application process handles messages, generates new program-controlled commands, and transfers them to the upper layer through the output and forwarding process.

2. Output and forwarding processes

- a. Application data generated by the application process are sent to the network layer.
- b. The network layer wraps the application data, generates the command source package and sends it to the data link protocol sublayer. Besides, the network layer receives the command source packets from the parsing process and forwards them to the data link protocol sublayer.
- c. The data link protocol sublayer takes following steps to route and forward received transfer frames and packets.
 - (1) Searching the frame routine table according to the VCID of the transfer frame or the APID of the packets.
 - (2) Finding the appropriate physical address of the bus, converting the frame or the packet into a sequence of messages and forwarding it to the sync. And channel coding sublayer.
- d. The sync. And channel coding sublayer sends out the sequence of messages through the bus.

2.5 Comparison of Telecommand Implementation Mechanism

Compare to traditional telecommand implementation mechanism, the new layered implementation mechanism proposed in this paper has advantages on almost all aspects. Table 1 shows the result.

Table 1. Comparison of telecommand implementation mechanisms

	Layered implementation mechanism	Traditional implementation mechanism
Telecommand protocol	Follows telecommand space data link protocol	Follows PCM telecommand protocols, which are non-standard protocols
Multi-user support	Supports multi-user through segmentation Has good scalability	Supports multi-user through customized format Has no scalability
Inter-spacecraft telecommand forwarding	Has spacecraft identifier. Supports forwarding telecommand multiple times among multiple spacecrafts	Has no spacecraft identifier Supports forwarding telecommand only once between two spacecrafts
Inter-spacecraft telecommand forwarding features	Forwards entire frame directly, doesn't need to parse frame, has high efficiency and low delay	Needs to parse frame and strip header, has low efficiency and high delay
Device-to-device command forwarding	Supports forwarding device-to-device command multiple times among multiple spacecrafts	Supports forwarding device-to-device command only once between two spacecrafts
Manual command forwarding	Supports forwarding manual command multiple times among multiple spacecrafts	Supports forwarding manual command only once between two spacecrafts
Telecommand forwarding for new visiting spacecrafts	Can form new flow for data transmission dynamically by injecting the modified route table on board Doesn't need to upgrade software	Can't support, needs to upgrade software

Overall, the new mechanism has great advantages over the traditional telecommand implementation mechanism in terms of protocol standardization, system flexibility, scalability, and extensibility.

3 Application Validation

The layered implementation mechanism proposed in the paper for telecommand and device management has been applied to the DMS of a large spacecraft assembly. The assembly consists of three independently orbiting spacecrafts which are interconnected by the docking buses. Each spacecraft is equipped with a data managing device as the bus controller (BC) and all the three data managing devices have adopted the layered implementation mechanism. The bus topology and information flow are shown in Fig. 4.

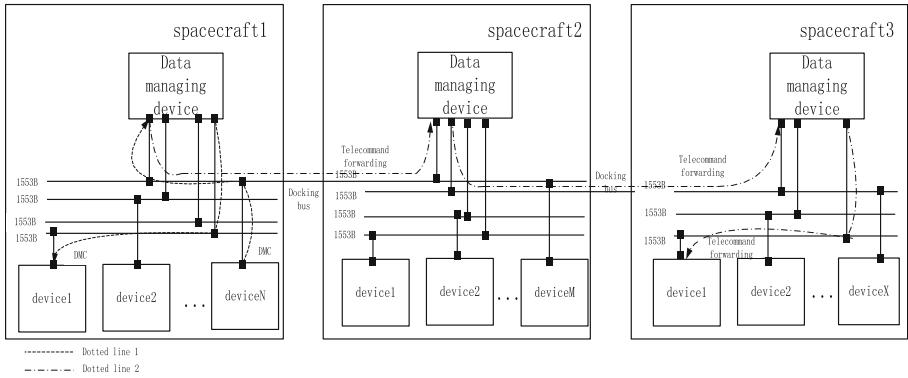


Fig. 4. The bus topology and information flow

We run the three data managing devices in laboratory and use simulator software to simulate RTs on the 1553B networks of the three spacecrafts. To verify the new mechanism can work correctly, we keep the volume of data transmitted among the three data managing devices and simulated RTs the same as the volume of data in real orbiting system. The average volume of data transmitted on each bus is about 200–300K bps.

The dotted line 1 in Fig. 4 shows the example data flow of transmitting the DMC from device N to device 1 within the spacecraft 1. The DMC issued by device N is collected by the data managing device firstly, and then is handled as below:

1. The DMC is decoded by the sync. And channel coding sublayer. A transfer frame is extracted and sent to the data link protocol sublayer in the parsing process.
2. One or more command source packets are extracted from the transfer frame and sent to the network layer in the parsing process.
3. The command source packets are transferred to the network layer in the output and forwarding process.
4. The command source packets are forwarded to the sync. And channel coding sublayer in the output and forwarding process.

5. The command source packets are encoded to bus messages and then be output to the bus.
6. Device 1 receives messages from bus and handles it.

According to the data collected in laboratory, the latency of transmitting DMC between two devices in the same spacecraft is about 20–80 ms.

The dotted line 2 in Fig. 4 shows the example data flow of transmitting telecommands from spacecraft 1 to device 1 in spacecraft 3 via spacecraft 2. The uplink telecommand is received by the data managing device of spacecraft 1 firstly, and then is handled as below:

1. The telecommand is decoded by the sync. And channel coding sublayer. A transfer frame is extracted and sent to the data link protocol sublayer in the parsing process.
2. The transfer frame is forwarded to the data link protocol sublayer in the output and forwarding process.
3. The transfer frame is forwarded to the sync. And channel coding sublayer in the output and forwarding process.
4. The transfer frame is encoded to bus messages and then be output to the bus.
5. The data managing device of spacecraft 2 receives the uplink telecommand from bus and repeat step 1 to 4 to forward the uplink telecommand to spacecraft 3.
6. The data managing device of spacecraft 2 receives the uplink telecommand from bus and repeat step 1–4 to forward the uplink telecommand to spacecraft 3.
7. The data managing device of spacecraft 3 receives the uplink telecommand from bus and repeat step 1–4 to forward the uplink telecommand to device 1
8. Device 1 in spacecraft 3 receives messages from bus and handles it.

According to the data collected in laboratory, the latency of transmitting telecommand between two spacecrafts is about 120–550 ms.

The result of application validation shows that the DMS adopted the layered implementation mechanism can forward DMC and telecommands among multiple devices and multiple spacecrafts steadily and reliably, and the latency of command transmission is low. It proves that the layered implementation mechanism can satisfy the needs of command transmission in large scale spacecraft assembly.

4 Conclusion

The layered implementation mechanism for telecommand and device management proposed in the paper has been successfully applied to a large spacecraft assembly. With the new mechanism, the commands for each spacecraft in the assembly can be injected through a unified physical channel and be transferred to the destination spacecraft in real time through the parsing process and the output and forwarding process. All devices connected to the on-board bus network of the assembly can send and receive commands mutually. All the manned ships, cargo ships and other visiting spacecrafts that will be docked with the assembly later can also interact with the on-board assembly seamlessly. On the basis, the complex networks of multi-ship, multi-cabin, multi-spacecraft assembly can be built finally, and the much more complex functions of the space information systems will be realized.

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