Design and Implementation of Teleoperation System for Deep Space Mission

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Abstract—**Critical elements in deep space exploration reside in that the rover travels over the surrounding undetermined planet surface environment and conducts scientific exploration under the control of ground center via teleoperation system. Such a teleoperation system plays a vital role in the whole deep space mission. The teleoperation system mainly includes four important capabilities: reconstruction of lunar terrain, vision-based localization, path planning for safe movement and planning verification of motion instruction. And it is composed of four functional modules, which are Two-Dimensional (2D) data display, Three-Dimensional (3D) data display, manipulation of geometric elements and communication between different configuration items by broadcasting Extensible Markup Language (XML) message. Based on the development and engineering application experience of teleoperation system for multiple deep space missions, this paper focuses on the requirement analysis, system design, system implementation and engineering verification to introduce the teleoperation system that has been applied in Chang'E-3 (CE-3) and Chang'E-4 (CE-4) lunar exploration missions successfully. In the final part of this paper, two key factors of open source and cross platform have been put forward for the development of teleoperation system. This research will have a significant impact on the application of teleoperation system in subsequent moon exploration missions and the future Mars exploration program.**

Index Terms—**Deep space mission, Chang'E-4, Teleoperation system, XML**

I. Introduction

DEEP space mission is the general term employed to the exploration of Moon and the celestial bodies or deep space beyond the Moon [1]. The rover travels over the surrounding undetermined planet surface environment and conducts scientific exploration under the control of ground center via teleoperation system. Such a teleoperation system is indispensable during the rover travels over the undetermined planet surface, which has an irreplaceable role in a deep space mission. Since the US launched the first lunar probe in August 1958 to China's CE-4 lunar probe soft landing on the far side of the Moon in January 2019, there are more than 240 deep space exploration missions that have been accomplished. At the same time, a lot of techniques such as hard landing, soft landing, teleoperation of rover and automatic sampling have been verified successfully [2]. However, due to the technologies such as computers, artificial intelligence and communications are still immature; it is hard to conduct fully autonomous scientific exploration in deep space mission in a short term [3]. In addition, it is highly dangerous that astronauts perform space missions out of spacecraft in the harsh aerospace environment.

At present, the teleoperation system has been successfully applied to the rendezvous and docking of space station or spacecraft, and the teleoperation control of the rover which travels over the surface of the Moon and Mars. In the whole deep space mission, the teleoperation system belongs to the ground application system, which provides an integrated business processing platform for the planet rover. What's more, the ground control center can set the parameters of various configuration items and monitor the running state of planet rover in real time through teleoperation system. This paper focuses on the development situation of teleoperation system, requirement analysis, system design, system implementation and engineering verification to introduce the teleoperation system that has been applied in CE-3 and CE-4 lunar exploration missions.

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II. Development Situation of Teleoperation System

The planet rover conducts scientific exploration under the control of ground center via teleoperation system, which not only avoids the damage that the astronauts would suffer when working in the harsh space environment, but also reduces the mission cost and improves the efficiency of exploration. At present, only three countries, the US, Soviet Union and China have the ability to control the rover to travel over the surrounding unstructured surface environment of Moon or Mars. Among all the deep space missions, the teleoperation systems can be subdivided into the following four kinds:

A. Teleoperation System for Apollo Manned Lunar Mission

The Lunar Roving Vehicle (LRV) is a battery-powered four-wheeled rover used on the Moon in the last three missions of the Apollo program (15, 16, and 17) during 1971 and 1972. LRV was transported to the Moon on the Apollo lunar module of each successive mission. It could carry two astronauts, their equipment and lunar samples. The teleoperation system of LRV consists of three functional modules: task instruction control module, system interactive module and rover condition monitoring module. With the support of scientific computing, the teleoperation system has completed data detection, space environment analysis, rover path planning and so on. During the lunar working section, the manned lunar rover was controlled by the astronauts. That is, the communication or the teleoperation control between the ground and the lunar rover were responded by the astronauts directly.

B. Teleoperation Systems for Mars Exploration Mission

During the past decades, the US has launched multiple deep space probes to land on Mars, which realizes the extra large time delay teleoperation control between Mars and Earth. Because of the time delay, the Mars rover must be more automated than the lunar rover. So its teleoperation control mode is ground teleoperation plus rover semi-autonomy [4]. During the rover travels over the Mars, the ground control center cannot control the Mars rover in real time. Instead, the ground control center can only communicate with the Mars rover periodically. Therefore, the Mars rover works in the “Move-Pause-Move” teleoperation control mode. And its semi-automatic ability is mainly reflected in automatic travel, emergency and resource management. Once in an emergency, it will initiate a safe mode and wait for the ground control center to resend the control instruction. The teleoperation system for Mars exploration mission mainly completes the visualization of downlink telemetry data and the motion path planning of the Mars rover. The ground control center performs mission planning and generates control instructions based on the downlink telemetry data. Besides, the ground control center sends instruction sequence to the Mars rover each Mars day to control the motion of the rover in this Mars day and receives the telemetry data of the rover in the Mars night to generate the mission planning instruction sequence for the next Mars day. A control cycle takes about 18 hours. The teleoperation system mainly includes the following capabilities.

1) Process and display the image of the surface of Mars collected by the cameras carried by Mars rover. It mainly includes image quality optimization, panorama stitching, adjacent images matching, and detection point coordinate display.
2) Generate and send the motion instruction sequence of Mars rover. It mainly includes target points marking, path planning, and planning verification. The system not only simulates the Mars rover and Mars surface environment, but also provides a model of the energy consumption of the Mars rover. That is, the real-time feedback of execution results can be obtained by feeding the motion instruction sequence into the simulation system. In addition, the simulation system also provides three forms: resource chart, 3D display and image tracking map to view the simulation process and results.

C. Teleoperation System of Soviet Union Lunar Rover

In 1970, the Soviet Union launched the first lunar probe with a lunar rover. This is the first time that the lunar rover has scientifically explored the lunar surface environment. The rover worked for 11 months and walked 10.54km. In 1973, the Soviet Union launched the second lunar probe with the same lunar rover [5]. The rover worked for 5 months and walked 37km. The teleoperation control mode of the Soviet Union lunar rover is ground teleoperation. After the ground control center sending an instruction, it waits for the lunar rover to execute a motion instruction and returns the execution result to the ground control center. Then the ground control center performs error correction or continues to generate and send the motion instruction according to the returned execution result. The ground control group consists of commanders, pilots, navigators, directional antenna operators and parametric analysis engineers. They perform rover motion control through the teleoperation system according to the high resolution topographic images collected by the lunar rover with four panoramic cameras. The teleoperation system mainly completes lunar images reception, lunar obstacle recognition, obstacle distance measurement, accessibility analysis, antenna adjustment, path planning, and rover motion control instruction generation and so on. All motion control of the rover is completed by the ground control center based on the telemetry data such as the lunar images. This control mode reduces the load of the information processing system on the lunar rover greatly. However, it leads to a time delay of approximately 10s when receiving and transmitting the telemetry data.

D. Teleoperation System of China Lunar Rover

In December 2013, China launched the CE-3 lunar probe with a lunar rover to land on the Moon. In December 2018, China launched the CE-4 lunar probe with the same lunar rover to land on the far side of Moon successfully [6]. In CE-3 and CE-4 lunar exploration missions, the ground control center adopted the combination mode of ground teleoperation and rover semi-autonomy to control the rover in the surrounding undetermined lunar surface environment. The teleoperation system provides a unified interactive interface for the related configuration items in the lunar working section. In addition, it enhances the measurement and control means for the centralized and efficient lunar working. Supported by the data interaction and business processing of the related background configuration items, the teleoperation system can accomplish the business operations such as lunar surface images analysis, 3D lunar terrain reconstruction, detection point location, exploration task planning, planning verification and so on. This teleoperation system will be illustrated in detail below.

III. Requirement Analysis

Due to the limited load of lunar rover, it only has basic autonomous control capability now. So, the lunar rover must be controlled by the ground control center via teleoperation system. The data of lunar surface and the position and motion posture data of lunar rover can be collected through the environment perception equipment such as the surveillance cameras carried by the lunar rover. The ground control center would carry out the reconstruction of lunar terrain, the vision-based localization, the path planning for safe movement and simulate the motion state of the lunar rover in a virtual lunar rover control environment to verify that the motion instruction of the next moving target is safe. Then, the optimal motion control instruction is remotely injected into the lunar rover to control the lunar rover on the Moon.

A. Business Requirements

The architecture of teleoperation system is based on the mission goals of China deep space exploration project. It takes the mission network architecture, data management system, application service system and other components into consideration to avoid the incompatibility. Then a unified standard system that each component must follow has been established to ensure the efficient operation of the whole deep space mission. There are four main configuration items including reconstruction of lunar terrain, vision-based localization, path planning and planning verification since receiving telemetry data to generate the optimal motion instruction. The whole teleoperation system exchanges data based on XML message service. The producers and consumers of XML message generate or parse XML message following a unified message interface document. The workflow of teleoperation system is shown in Fig 1.

Reconstruction of lunar terrain is the basis of vision-based localization, path planning and planning verification [7]. It analyzes lunar surface images data, lunar surface images preprocessing, adjacent images matching, stereo images matching, 3D lunar terrain generation and 3D lunar terrain publishing to provide basic 3D lunar terrain for other configuration items through teleoperation system.

Vision-based localization takes sequence images at different sites through the binocular navigation cameras that pre-installed on the lunar rover accurately [8, 9]. It calculates the position and motion posture data of the lunar rover by images matching and the 3D spatial relationship of images matching feature points. Firstly, the images matching feature points are extracted from the left camera images taken by the camera at different sites and the corresponding feature points are extracted from the right camera images according to these feature points in the left camera images. Then these feature points are considered as observation points. Finally, the position and motion posture data of lunar rover on the current site can be calculated according to the photogrammetric principle.

Path planning is a critical step for the lunar rover to avoid obstacles and arrive at the target position safely when it traveling over the undetermined surface environment of the Moon [10]. First of all, the lunar physical environment must be abstracted into a mathematical model that can be understood and expressed by computer [11]. It converts the lunar physical environment into a connected graph for searching path according to the known lunar environmental information. Then, an optimal path without obstacles from the starting position to the target position is found in the environment connected graph based on the global path planning algorithm with unique motion requirements. Path planning includes exploration mission planning, motion path planning and motion planning of space manipulator.

Planning verification can be subdivided into digital verification and physical verification [12]. It will lead to the failure of deep space mission if the motion instruction of rover is incorrect. What’s more, the motion control instruction and the detection target instruction are generated in real time through teleoperation system. Therefore, the ground control center must plan and verify the instruction to ensure the safety of the lunar rover. Digital verification drives the 3D lunar rover model in the virtual lunar rover control environment according to the motion instruction to get the verification results. Physical verification sends motion instructions to the lunar rover in the ground test environment and observes the motion effect of the lunar rover to assess the correctness of the motion instruction.

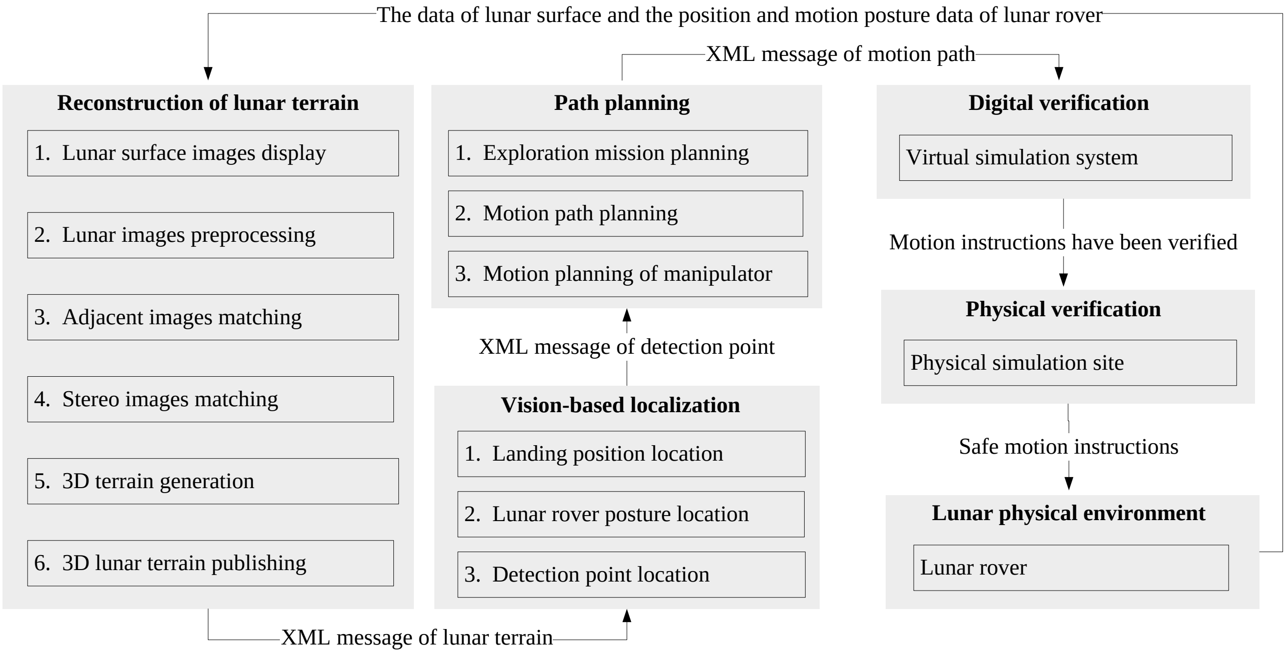

Fig. 1. The workflow of teleoperation system.

B. Functional Requirements

Corresponding to the business requirements in the last Section *Business Requirements*, the teleoperation system includes the following four functional modules.

2D Data Display

1) Display the 2D lunar surface images in the image display window by automatically receiving or manually dragging.
2) The image display window should support single viewport or multi-viewports synchronization display.
3) The image display window should support image scaling, dragging, ascending or descending order, layering and quality optimized display.
4) Real-time display of geometric elements and the properties of these geometric elements including points, lines, ellipses, rectangles, polygons and curves.
5) Real-time display of the position data and joint angle parameters of the lunar rover for the current probing point in table.
6) Real-time display the distance between the end of probing mechanism and the lunar surface.

3D Data Display

1) The display of 3D point cloud. Users can select points on the 3D point cloud and set the size and color of the selected 3D space points.
2) Highlight display of the selected space points on the 3D point cloud.
3) The display of 3D lunar terrain, the dynamic display of lunar rover model and the display of space manipulator motion planning.
4) The display of the lunar rover model and terrain based on planning verification result.
5) The panoramic display of the 3D lunar rover model, 3D lunar terrain model, reachable space points and pre-selected probing points.
6) The display of space manipulator collision detection.
7) The viewpoint transformation display of the 3D data by mouse or keyboard events such as rotation, translation, and dragging.

Manipulation of Geometric Elements

1) Users can insert geometric elements in the lunar image displayed in the window by enlarging mode and mark them accurately. It mainly includes inserting a single geometric element and inserting multiple matching geometric elements.
2) Users can select geometric elements on 2D lunar image and 3D point cloud by enlarging mode and mark them accurately. It mainly includes selecting a single geometric element and selecting multiple matching geometric elements.
3) Users can insert point, line, ellipse, polygon and other geometric elements on the 3D model or 2D image for data identification and interaction.
4) Users can measure the length, width, area or other parameters and send these data to relevant configuration items to start corresponding calculation.
5) Users can modify the result of reconstruction of lunar terrain, vision-based localization, path planning and planning verification.
6) Set system parameters.

Communication between Different Configuration Items

The teleoperation system mainly includes four different configuration items. Each configuration item exchanges data by matching the message number of XML message with other configuration items. Each configuration item produces or consumes XML message following the unified message interface document. A standard XML message consists of a message header and a message body. The message header contains various information including XML message producer, host name, sending time, message number and so on. The message body contains information of file name, the attributes of geometric elements, the running state of the lunar rover and so on. The XML message is broadcast in the global segment and each configuration item consumes XML message by subscribing to the pre-agreed message number.

IV. System Design

Corresponding to the functional requirements in Section *Functional Requirements*, the teleoperation system mainly consists of four functional modules. Each module contains several sub-functional modules. The open source and cross-platform software development kit Qt is used to develop the functions of system interface design, 2D data display and manipulation of geometric elements [13]. OpenSceneGraph (OSG), an open source and cross-platform 3D graphics toolkit with excellent performance, is utilized to realize the display of 3D terrain, rover model, path planning and planning verification of patrol mechanism [14]. The XML message is used to communicate between different configuration items [15]. Qt is based on C++, which supports multiple platforms including Microsoft Windows, Linux, Mac OS, Android, and most mobile or embedded platforms. Qt mainly consists of Qt Creator, Qt designer, Qt assistant and Qmake. And it mainly includes graphical user interface design, 2D/3D graphics rendering, OpenGL, XML file parsing, etc. The OSG is written entirely in C++ and OpenGL. It can run on all Windows platforms, Linux, IRIX, Solaris, HP-UX, AIX and FreeBSD operating systems. XML is an extensible markup language that defines a set of rules for encoding documents in a logical format that is both human-readable and machine-readable. XML has come into common use for the data exchange over the Internet. It is worth mentioning that Qt, OSG and XML are all open source and cross-platform. So the teleoperation system does not depend on any commercial system or third-party library. What’s more, it can run on all mainstream operating systems.

A. Communication between Different Configuration Items

Each configuration item produces or consumes XML messages according to the unified message interface document to communicate with other configuration items in teleoperation system. For example, a simple point has been selected in the left image display window and its 2D coordinate "x, y" need to be broadcast in the global segment, and the pre-agreed message number is 10284. The corresponding XML message is as follows.

```
<root>
  <number>10284</number>
  <point windows= "left">
    <x>102.55</x>
    <y>18.63</y>
  </point >
</root>
```

As shown in Fig 2, its root element is <root>. All the elements in the XML message are included in the element <root>. The element <point> consists of two sub-elements: <x> and <y>. The values of <x> and <y> are 102.55 and 18.63. The attribute of element <point> is "left".

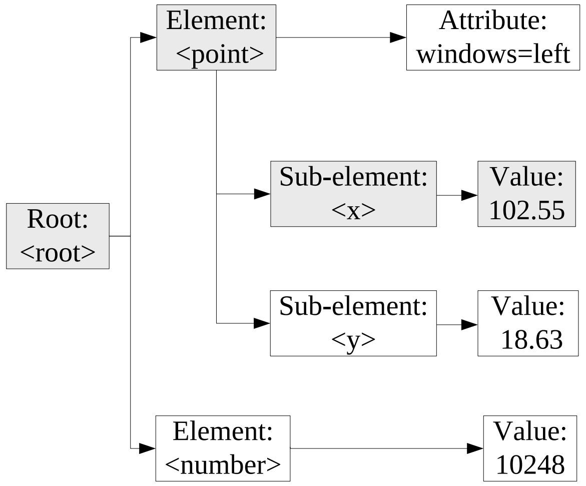

Fig. 2. The logical structure of the XML message.

Generally, the communication between different configuration items is divided into XML message parsing function and XML message generating function. Parsing a XML message needs four parameters: *A*, *B*, *C* and *D*. The meanings of these parameters and their actual values when parsing the value of sub-element <x> in the above XML message (Gray background in Fig 2) are illustrated in Table I. Generating an XML message also needs four parameters and the principle is similar to parse the XML message. So it is not repeated here.

TABLE I
THE MEANING AND ACTUAL VALUE OF EACH PARAMETER

Parameter	Meaning	Actual value
A	Message number	10284
B	Parsing field	root/point/x
C	Variable	102.55
D	Parsing result	Success

B. 2D Data Display

2D data mainly consists of lunar images and system parameters. And the image display window should support image scaling, dragging, sorting and layering display. The teleoperation system needs five parameters: *A*, *B*, *C*, *D* and *E* to display a lunar image in the window. And the actual values of the five are parameters got by the XML message parsing function in Section *Communication between Different Configuration Items*. For example, the XML message that displays a lunar image in deep space missions is as follows.

```
<root>
  <number>10285</number>
  <File name>D:/image/lunar_image.jpg</File name>
  <2D coordinates>
    <x>00.00</x>
    <y>00.00</y>
  </2D coordinates>
  <Width>1024.00</Width>
  <Height>2048.00</Height>
  <Result>Success</Result>
</root>
```

The meaning and actual value of each parameter have been illustrated in Table II. The "2D coordinates" maintains the upper-left coordinates of the display area. The "width" and "height" maintain the width and height of the image display window.

TABLE II
THE MEANING AND ACTUAL VALUE OF EACH PARAMETER

Parameter	Meaning	Actual value
A	File name	D:/image/lunar_image.jpg
B	2D coordinates	00.00, 00.00
C	Width	1024.00
D	Height	2048.00
E	Result	Success

C. 3D Data Display

The lunar rover model is divided into multiple sub-models, and then these sub-models are assembled logically for independent motion. As shown in Fig 3, the lunar rover is divided into five sub-models: Main model, Sub-model1, Sub-model2, Sub-model3 and Sub-model4. Each sub-model is a separate file saved in the computer.

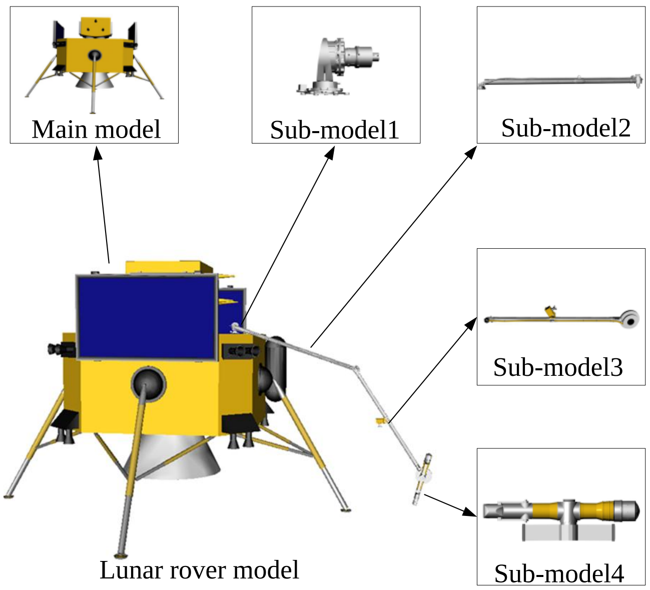

Fig. 3. The display principle of 3D lunar rover.

Loading and displaying a 3D lunar rover model need four parameters: *A*, *B*, *C* and *D*. The meanings of these parameters are illustrated in Table III. Their actual values are got by the XML message parsing function just like the 2D data display. The "3D coordinates" maintains the central coordinates of the 3D model. For example, the XML message that displays the main model in Fig 3 is as follows.

<root>
<number>10286</number>
<File name>D:/model/main model.3ds</File name>
<3D coordinates>
<x>512.00</x>
<y>450.00</y>
<z>352.00</z>
</3D coordinates>
<Child model >sub-model1</Child model>
<Result>Success</Result>
</root>

TABLE Ⅲ
THE MEANING AND FUNCTION OF EACH PARAMETERS

Parameter	Meaning	Actual value
A	File name	D:/model/main model.3ds
B	3D coordinates	512.00, 450.00, 352.00
C	Child model	sub-model1
D	Result	Success

D. Manipulation of Geometric Elements

There are four main kinds of geometric elements, including point, line, polygon and ellipse for marking, interactive computing and measurement in teleoperation system. And the manipulation of geometric elements mainly includes insertion, deletion, selection and movement. All geometric elements are manipulated through the interaction between the mouse and teleoperation system or parsing XML message. For example, the users need to mark two detection points on the lunar image. There are four parameters *A*, *B*, *C*, *D*, *E* and *F* that need to be defined to insert a point. The corresponding XML message is as follows.

<root>
<number>10287</number>
<Geometric element>1</ Geometric element>
<point number>2</point number>
<point>
<id>1</id>
<3D coordinates>
<x>12.55</x>
<y>18.63</y>
<z>15.75</z>
</3D coordinates>
</point >
<point>
<id>2</id>
<3D coordinates>
<x>2.55</x>
<y>46.63</y>
<z>33.75</z>
</3D coordinates>
</point >
</root>

The "Geometric element" maintains the type of geometric element, that "1" indicates it is point. The "point number" holds the number of points in the XML message. The meaning and actual value of each parameter have been illustrated in Table Ⅳ.

TABLE Ⅳ
THE MEANING AND ACTUAL VALUE OF EACH PARAMETER

Parameter	Meaning	Actual value	
		First point	Second point
A	Element type	point	
B	Point number	2	
C	Point id	1	2
D	3D coordinates	12.55, 18.63,15.75	2.55, 46.63, 33.75

V. IMPLEMENTATION AND VERIFICATION

In the CE-3 and CE-4 lunar exploration missions, the teleoperation system completes all the teleoperation control tasks during the lunar working section successfully. The teleoperation system provides a control platform for the lunar exploration mission by receiving real time data of lunar images and the position and motion posture data of the lunar rover during the whole lunar exploration mission [16]. It conducts scientific exploration according to the following steps.

Reconstruction of Lunar Terrain

1) The teleoperation system receives telemetry data from the lunar rover, and then calls the 2D image display function to display 2D lunar images.
2) Call the XML message parsing function to parse the XML message with point cloud data to obtain the number of points and the coordinate of each point.
3) Call the manipulation of geometric elements function to insert points and then connect the adjacent points to generate 3D mesh lunar terrain.

The 3D mesh lunar terrain is shown in Fig 4.

Vision-based Localization

1) Call the XML message parsing function to parse the XML message with 2D image data. And then the system gets the 2D image file name that need to be displayed.
2) Adjust the brightness and contrast of the lunar image to optimize the quality of the original lunar image. The interface of image preprocessing of teleoperation system is shown in Fig 5. On the left is the original lunar image and on the right is the optimized image after adjusting its brightness and contrast.
3) Call the manipulation of geometric elements function to insert points in the lunar images displayed in step (2). Then the point ID and the coordinates of each point were displayed in table. The table "Point" on the left of Fig 6 displays the coordinate information of these points.
4) Call the XML message generating function to generate the XML message with point coordinates in step (3).
5) Broadcast the XML message in the global segment.

The interface of vision-based localization following the above steps is shown in Fig 6. The blue crosses in Fig 6 are the obstacles marked in step (3) and the green squares are the selected points for moving or deleting.

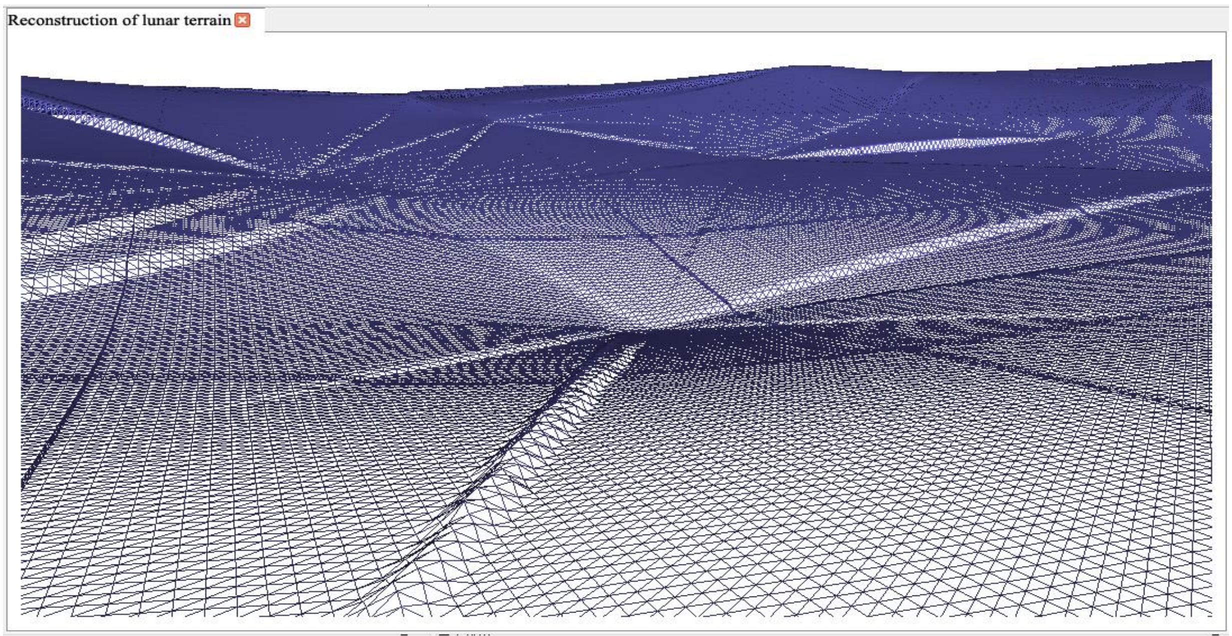

Fig. 4. The 3D mesh lunar terrain of teleoperation system.

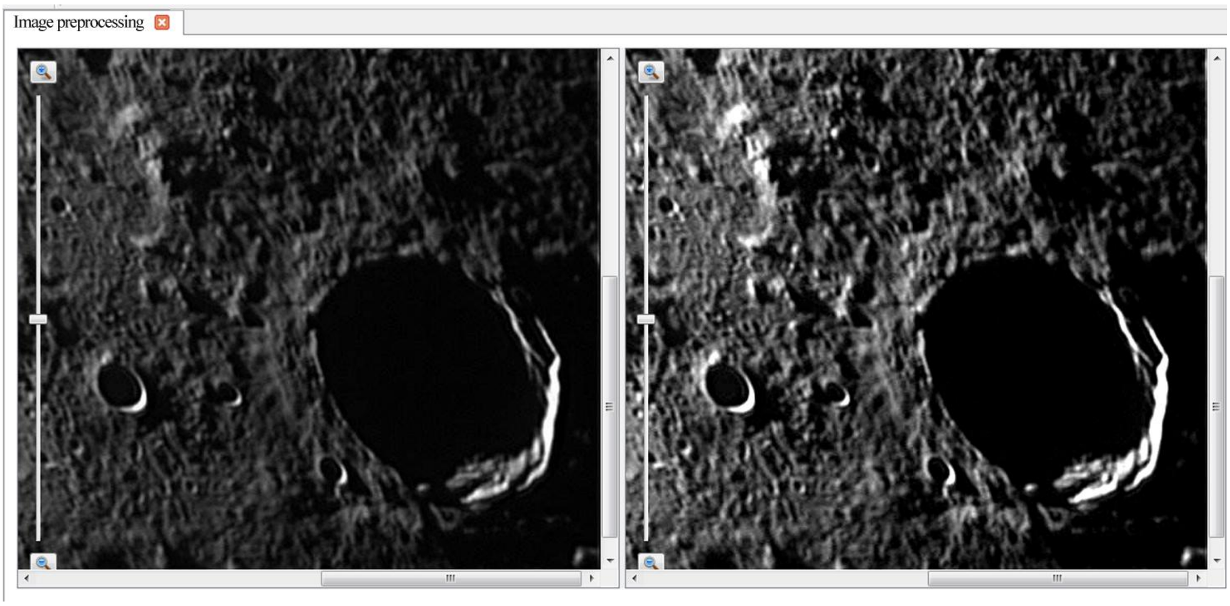

Fig. 5. The interface of image preprocessing of teleoperation system.

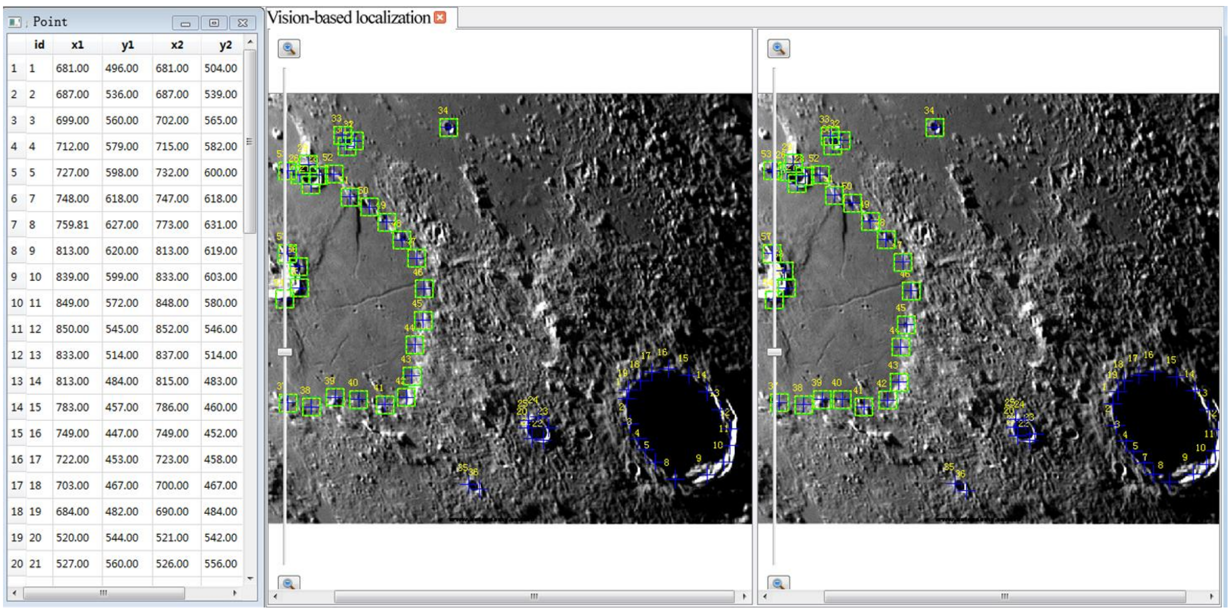

Fig. 6. The interface of vision-based localization for probing on the lunar surface.

Motion planning of space manipulator

1) The 3D lunar rover model is loaded and displayed in the display window by calling the 3D data display function. The 3D lunar rover model is composed of the main vehicle body model and four active joints. The four active joints are the child models of the main model.
2) Call the XML message parsing function to parse the XML message with the initial angle data, which can be used to set the initial position and posture of each active joint.
3) Click on the "+", "-", "Set", "Plan" and "Reset" buttons in Fig 7 to adjust the angle of each active joint.
4) Call the XML message generating function to generate the XML message with joint angle data in step (3).
5) Broadcast the XML message in the global segment. Then the XML message is saved in the local computer before being verified. The XML message saved in the local computer is as follows.

<root>
<number>10289</number>
<sub model number>4</sub model number>
<sub model>
<id>1</id>
<angle>-100</ angle>
</sub model >
<sub model>
<id>2</id>
<angle>18</ angle>
</sub model >
<sub model>
<id>3</id>
<angle>38</ angle>
</sub model >
<sub model>
<id>4</id>
<angle>48</ angle>
</sub model >
</root>

The motion planning interface of space manipulator following the above steps is shown in Fig 7. The red rectangular area in Fig 7 is the angle information.

VI. Conclusion

As a regular information processing system for deep space mission in China, the teleoperation system introduced in this paper has been applied in the teleoperation control of the lunar rover in CE-3 and CE-4 lunar exploration missions successfully. Moreover, it will be promoted in CE-5 lunar exploration mission and the Mars exploration mission. The teleoperation system realizes the automatic teleoperation for safe movement of the lunar rover, improves the control efficiency, ensures the safety of the lunar work, and enriches the verification means and the simulation capabilities of the ground teleoperation control center.

At present, the development of information processing system for deep space mission in most countries is in its early phase. Based on the development and engineering application experience of teleoperation system for multiple deep space missions, there are two suggestions for the development of aerospace information processing system.

1) The capability of deep space mission is a key indicator of national defense strength. So the aerospace information processing system must be self-developed with independent intellectual property rights. The development support environment and survival support environment of the teleoperation system are all based on the China's NeoKylin operating system [17]. What's more, the teleoperation system does not depend on any commercial system or third-party library, which ensures the independence and controllability of the system.
2) All the software development kits of the teleoperation system are cross-platform and open source [18]. Cross-platform ensures that it is fully compatible with the mainstream operating system. Besides, open source ensures that it is independent of any commercial systems.

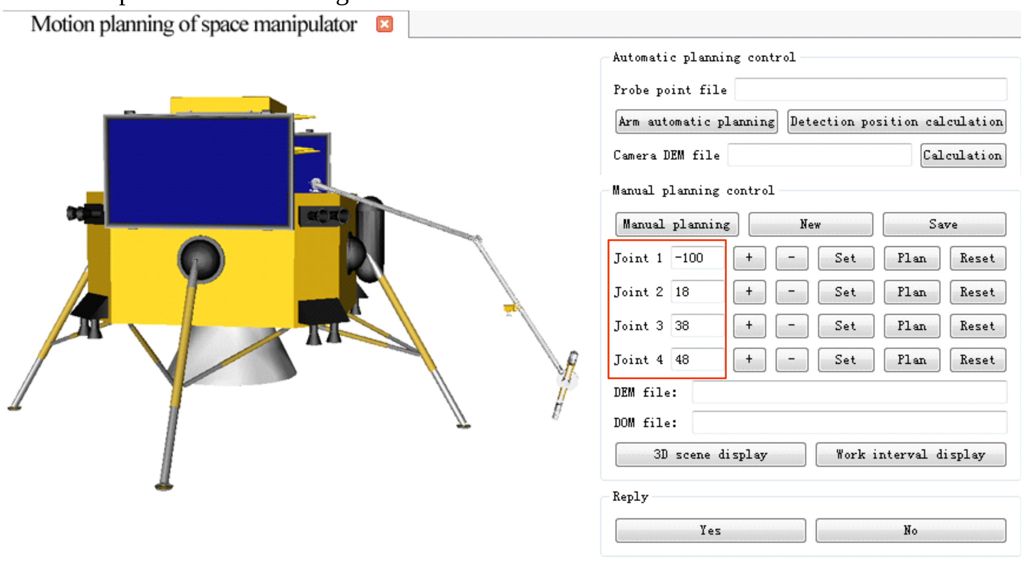

Fig. 7. Motion planning interface of space manipulator for probing on the Moon (Unreal Model).

According to China's Military Software Product Evaluation standard (GJB2434A-2004) [19], the teleoperation system is A-level military software. Therefore, it must be verified and validated by formal method. The formal verification is based on formal description. But now all the requirements and design documents of teleoperation system are described in natural language. So, it is necessary to describe and verify it through formal method [20, 21]. This will be the future research focus.

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