Research on Rapid 3D Reconstruction for Teleoperation in Manned Lunar Exploration Mission

Lin Tian[1](✉), Yinuo Sheng[1], Xisheng Li[1], Pengcheng Wang[1], and Jiwu Wang[2]

[1] Beijing Institute of Spacecraft System Engineering, Beijing 100094, China
`lucksonner@163.com`
[2] Beijing Jiaotong University, Beijing 100044, China

Abstract. Teleoperation can greatly improve the whole mission benefits of manned lunar exploration, while it is necessary to provide a real and effective environment for astronauts through rapid 3D reconstruction. The requirements of teleoperation and the characteristics of the operated objects in the future manned lunar exploration mission are analyzed. According to the characteristics of the lunar environment, a 3D rapid reconstruction scheme based on the combination of motion structure recovery and binocular vision is proposed, and the proposed scheme and its accuracy are verified through ground tests.

Keywords: Manned Lunar Exploration · Lunar Teleoperation · Rapid 3D Reconstruction · Structure From Motion · Binocular Vision.

1 Preface

1.1 A Subsection Sample

Lunar has already become the primary target of human deep space exploration since the new century, and several countries and institutions have declare their lunar exploration plans. Teleoperation means controlling robots remotely to complete relatively complex operations in a site far away from the operator. In the manned lunar exploration mission, teleoperation can support astronauts controlling robots to reach dangerous sites and carrying out deep exploration works. For large-scale exploration, high-intensity and repetitive works, astronauts can focus on the control operation for a long time in a safe and comfortable environment with good mental state. Meanwhile, this can help avoiding time consumption and risks of pressure cabin entry and exit, which reducing the requirements of astronauts' personal characteristics. Teleoperation can also support multiple operators to cooperate at different levels, which greatly improves the whole benefits of mission. In order to support teleoperation, it is necessary to build a 3D environment of the operation site through VR technology to provide operators with a strong sense of immersion and comprehensive and systematic task information.

© ICST Institute for Computer Sciences, Social Informatics and Telecommunications Engineering 2023
Published by Springer Nature Switzerland AG 2023. All Rights Reserved
R. Li et al. (Eds.): MOBILWARE 2022, LNICST 507, pp. 91–105, 2023.
https://doi.org/10.1007/978-3-031-34497-8_8

Rapid 3D reconstruction of environment is the basis of high-quality and high-efficiency lunar teleoperation. It needs to provide effective environment and information of lunar robot and environment for astronauts with limits of computing and communication resources. This paper investigates and analyzes the situation of lunar teleoperation missions. Following the analysis of the teleoperation requirements of manned lunar exploration missions, a fast 3D environment reconstruction method suitable for the characteristics of lunar environment and the operation of lunar robots is proposed, while the accuracy is tested and verified by ground tests. The study can provide a useful reference for mission applications in the future.

2 Development of Lunar Teleoperation Technology

2.1 American Lunar Rover

In 1967, the U.S. ‘Surveyor-3’ lunar probe successfully landed on the lunar. It completed the lunar soil collection tasks under the control of the ground station, and realized the earliest space robot teleoperation in human history.

The Apollo-15/16/17 missions utilized the non-pressurized manned lunar rover (LRV), with a maximum distance of 36 km. The LRV was manually controlled by the astronauts. At the same time, the ground control center was remotely controlling at different berths based on TV images. The ground control personnel were divided into three task groups: task command and control, system operation and status monitoring. In addition, there were support groups such as lunar surface experiments (Fig. 1).

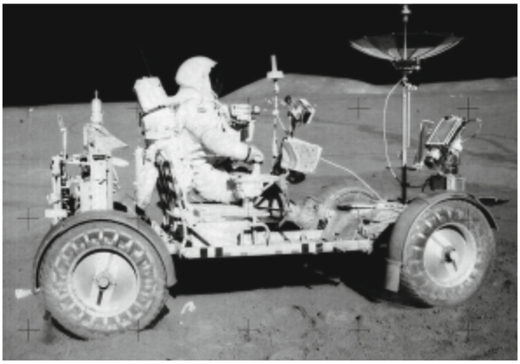


Fig. 1. Manned lunar rover in Apollo program.

2.2 Former Soviet Union Lunar Rover

The ‘Lunar-17’ lunar probe launched by the former Soviet Union in 1970 carried the lunar rover’Lunokhod-1’, which is the first lunar surface exploration activity carried out in the world. Lunar-17 worked for 11 months, and the walking distance of Lunokhod-1 reached 10.54 km, while the inspection area was 80000m2. In 1973, the Lunar-21 lunar probe with the Lunokhod-2 lunar rover was successfully launched. Lunokhod-2 carried out patrol and exploration activities, and its total walking distance was 37 km.

Both Lunokhod-1 and Lunokhod-2 adopted the ground teleoperation. Four panoramic cameras were used to collect high-resolution images. During the teleoperation from ground, five controllers sat in front of the television of ground control center, and the image of lunar surface returned by the lunar rover was displayed on the screen. According to these images, the driver sent commands to the lunar rover for moving slowly and avoiding from craters and obstacles. The camera protruding from the front of the rover body transmitted an image to the ground every few seconds. Although the quality was not so high, it could ensure that the ‘driver’ can avoid obstacles and move to the target position. When the lunar rover was in the ‘wandering’ state and unable to determine the subsequent moving path, it obtained higher resolution images through four panoramic cameras (Fig. 2).

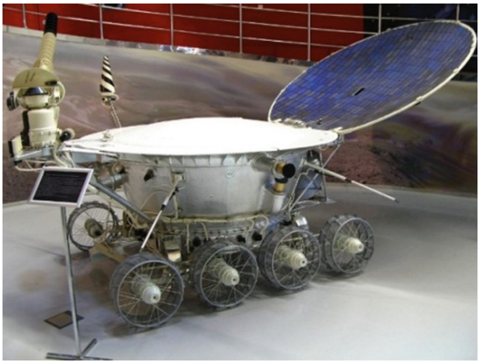


Fig. 2. Lunokhod lunar rover of the former Soviet Union

2.3 Chinese Lunar Rover

In December 2013, the Chang’e-3 (CE-3) lander successfully achieved a soft lunar landing. On December 15, the Yutu lunar rover realized the separation and mutual shooting of the two, which marked the success of the Chang’e-3 mission and became China’s first remote operation to patrol and detect an extraterrestrial object. The Yutu lunar rover worked in an unknown and complex environment on the lunar surface, and had two working modes: autonomous operation and remote operation. The ground mission support and teleoperation control system was the main system to realize the teleoperation, which was composed of 3D terrain construction, whole mission planning, detection cycle planning and other functional modules. The Yutu lunar rover restored and established 2D panoramic images and 3D topographic maps through a variety of algorithms, and realized task planning such as behavior sequence and travel path based on environment module, kinematics module and multi-constraint optimization algorithm. The Yutu lunar rover was equipped with panoramic camera, navigation camera and

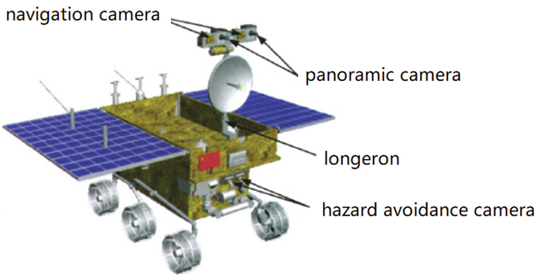


Fig. 3. Overall configuration of Chang'e-3 lunar lander with lunar rover 'Yutu'3

obstacle avoiding camera for imaging at different distances. In order to achieve stereo vision, all cameras used a dual camera configuration (Fig. 3).

In 2014, the CE-4 mission realized the first human landing on the back of lunar. The 'Yutu-2' lunar rover carried by it was optimized for ground teleoperation software based on CE-3, and the interactive interface was simplified through improving the level of automation. The CE-5 mission has realized the first lunar surface automatic sampling and return mission in China. Its surface sampling manipulator system mainly included two parts: lunar surface execution and ground remote operation, which were used for the ground test, test verification and on orbit operation of the surface sampling device (Fig. 4).

Fig. 4. CE-4 lunar surface moving traces of the rover Yutu-2

2.4 Summary

The problem of teleoperation delay on lunar surface is more serious. Considering the communication delay, information processing and transmitting, operator decision-making and other delays, the teleoperation delay is generally in the order of more than ten seconds. The continuous teleoperation of the lunar robot by ground operators in early missions is difficult, and the 'move wait' strategy can only be used. Although the system stability under large time delay is achieved, the system efficiency is greatly reduced.

In order to achieve continuous teleoperation under large time delay, prediction display and other technologies have been gradually developed, but the decision-making of operators needs the support of realistic 3D environment, and the immersion of operators is enhanced through virtual reality to improve the efficiency of teleoperation.

3 Requirement Analysis of Teleoperation for Manned Lunar Exploration

3.1 Teleoperation Task Analysis

According to the mission design of future manned lunar exploration mission, three types of teleoperation requirements can be summarized:

(1) Unmanned lunar exploration activities in manned lunar exploration

In the early stage of manned lunar exploration mission, it is necessary to carry out pre-exploration activities on the lunar surface through lunar robots, such as detailed exploration of candidate landing sites for manned lunar landing, in-depth exploration of the site selection of manned lunar research station or manned lunar base, and large-scale mobile exploration of the lunar surface. Remote operation the lunar robot can be done through a lot of ways, which not only ensures the efficiency and coverage of lunar exploration, but also reduces the cost and risk of subsequent manned lunar exploration missions.

(2) Human-machine joint detection in high risk areas

When astronauts carry out exploration activities on the moon, they will be threatened by the complex terrain, vacuum, extreme high and low temperatures, space radiation and other environmental threats on the moon. The man-machine joint working mode of astronauts in the pressured cabin + lunar robots can be utilized to reduce the risk of astronauts carrying out extravehicular activities.

(3) Large scale extravehicular operations centered on astronauts

When in the stage of large-scale system level lunar surface exploration or lunar resource development and utilization, it is necessary to establish a set of support system for large-scale extravehicular operations around astronauts, and take remote operation as the main task mode. Extravehicular large-scale operations are characterized by long duration, cooperative operation of multiple astronauts, and support of various resources during operation. If the astronauts are located in a suitable environment, the remote operation mode can avoid the inconvenience of fine operation when wearing extravehicular clothing, and can also establish a friendly and more convenient human-computer interaction channel through the mixed reality with the support of rich resources in the cabin.

3.2 Characteristic Analysis of Teleoperation Object

According to the results of teleoperation tasks and requirements analysis, the lunar teleoperation objects can be divided into two kinds: mobile type and operation type.

The mobile type mainly refers to the interaction between the operated object and the lunar terrain environment. The point of teleoperation is to measure and determine the relative pose relationship between the lunar robot and the surrounding terrain, and select the correct and safe mobile path (Fig. 5).

Fig. 5. Lunar surface moving robots

The operation type mainly refers to the interaction between the manipulator and the operated object. The key point of teleoperation is to measure the relative pose relationship between the manipulator and the operated object, and form the motion command of the manipulator (Fig. 6).

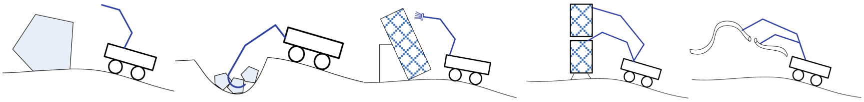


Fig. 6. Task types of single arm and double arm of lunar surface manipulators

4 Research on Rapid 3D Environment Reconstruction Method for Lunar Teleoperation

4.1 Comparative Analysis of Three-Dimensional Lunar Surface Reconstruction Methods

As an important branch of computer vision, 3D reconstruction technology can be divided into active acquisition and passive acquisition. The qualitative comparison of various 3D reconstruction methods is as follows (Table 1).

According to the characteristics of the lunar environment, binocular vision (BiV) and Structure from motion (SFM) are used for 3D reconstruction:

(1) When there are many feature points, SFM based method is used for 3D reconstruction;
(2) When there are few feature points, BiV is used for 3D reconstruction.

Table 1. Comparison of 3D reconstruction methods

Method	Automation level	Reconstruction effect
Shading method	Fully automated	The reconstruction effect is poor, vulnerable to illumination, and the robustness is poor
Photometric stereoscopic visual method	Can achieve a certain degree of automation	The reconstruction effect is good, affected by the light source, and the robustness is poor
Texture method	Fully automated	The reconstruction effect is poor, insensitive to light and noise, and has good robustness
Contour method	Fully automated	Depends on the number of contour images
Focusing method	Difficult to realize automatic reconstruction	It can calculate the depth of each point, and the reconstruction effect is better
Structure from motion method	Fully automated	The reconstruction effect is better. The more images, the better the reconstruction effect
Binocular vision	Fully automated	The reconstruction effect is better in the case of weak texture scene
Time flight method	Fully automated	The reconstruction effect is quite good
Structured light method	Fully automated	The reconstruction effect is quite good

4.2 3D Reconstruction Based on Moving Structure Restoration

SFM is a method to restore camera parameters and 3D information using numerical methods by detecting matching feature points in multiple uncalibrated images. The method has very low requirements for images, and can use video or even random image sequences for 3D reconstruction; At the same time, image sequences can be used to realize the self-calibration of the camera in the reconstruction process, which eliminates the pre-calibration steps of the camera; Moreover, due to the progress of various feature point extracting and matching technology, the robustness of method is also very strong.

Considering the limited field of view of a single monitoring camera, we can introduce the PTZ monitoring camera technology with target tracking, which can ensure that the robot is always within the effective range of the monitoring camera. At the same time, according to the new workspace of the mobile robot, we can control the scanning of the PTZ left, right and pitch, and provide a model for 3D environment reconstruction (Fig. 7).

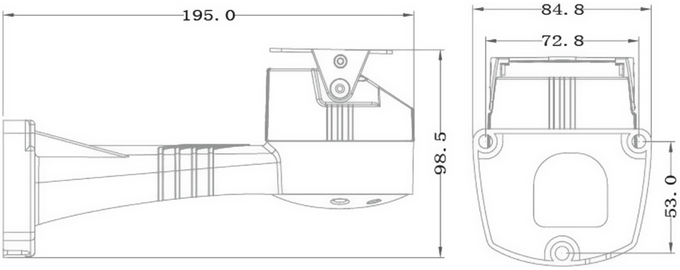


Fig. 7. Structural dimension and physical object of PTZ1

4.3 3D Reconstruction Based on Binocular Stereo Vision

Binocular stereo vision is a method to obtain depth information based on the parallax principle. It observes the same object from multiple perspectives and obtains images, then matches the images from different perspectives, calculates the depth information through the triangulation principle and the offset between corresponding points. This can obtain the distance between the object and the camera, and finally obtain the 3D information of the object. This method simulates the process of stereoscopic imaging of human eyes, and can achieve good results with low cost and simple system structure. It is widely used in product detection and quality control, and can collect images in an instant, so it is more effective for the measurement of moving objects.

5 Experiment and Accuracy Analysis of Rapid Reconstruction of 3D Environment

5.1 3D Reconstruction Test Based on Structure from Motion

The robot head pan tilt camera collects 2D images of the surrounding environment, imports the 2D images into the Meta-Shape software, and generates a 3D model through the process of aligning photos, establishing dense point clouds, generating meshes, generating textures. So the format is exported, and the ruler is placed in the environment. The scene accuracy is detected by the robot walking through a specified distance. Secondly, the model is imported into Unity 3D software for mapping, physical configuration and other operations. Finally, HTC vive glasses are configured to observe the scene (Fig. 8).

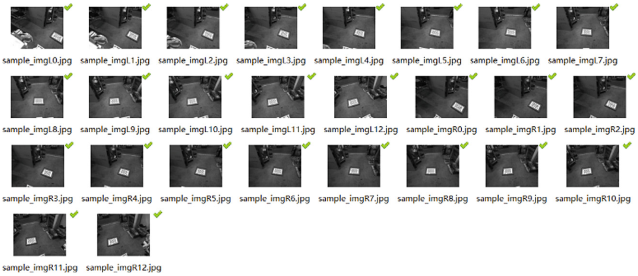


Fig. 8. Laboratory image collected by PTZ camera

The Meta-Shape software is imported for 3D reconstruction and accuracy analysis (Fig. 9).

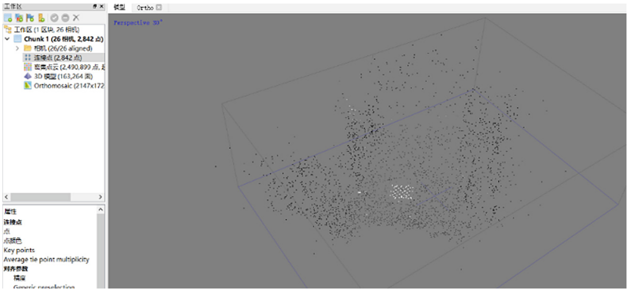


Fig. 9. Meta-Shape reconstruction diagram

3D environment is successfully reconstruct and observed with HTC Vive. By measuring the error between the grid distance detection of the calibration plate and the real environment, the test error is less than 1%, which can fulfill the requirement that the error of 10m scale 3D environment reconstruction of the lunar surface teleoperation task is less than 1% (Figs. 10, 11 and Table 2).

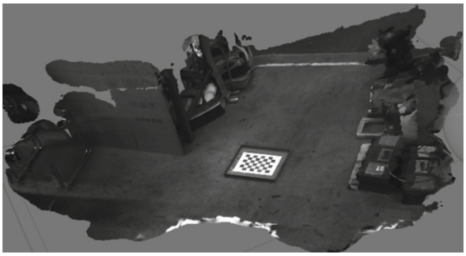


Fig. 10. 3D environmental map

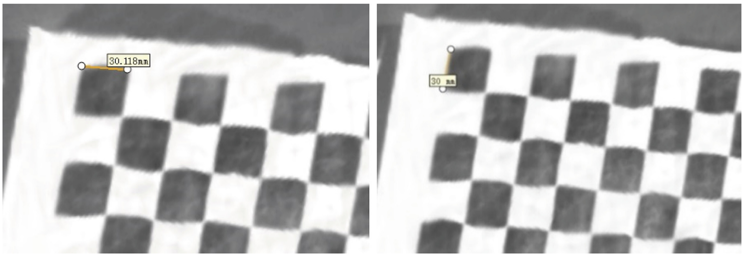


Fig. 11. 3D reconstruction error measurement results

Table 2. Accuracy error of 3D reconstruction

Line segment number	Direction	Measured value	Software measurements	Relative error	Relative error	Average error
		/mm	/mm	/mm		
1	level	30	30.118	0.118	0.393%	0.271%
2	level	30	30.235	0.235	0.783%	
3	level	30	29.891	-0.109	-0.363%	
4	vertical	30	30.001	0.001	0.003%	0.089%
5	vertical	30	29.841	-0.159	-0.530%	
6	vertical	30	30.238	0.238	0.793%	

Considering the task characteristics of no-obvious-features such as poor light and less texture information in the lunar environment, the meeting room and corridor area is selected as the on-site test environment with dark light and weak ground texture information. The 3D environment model is successfully reconstructed, as shown in the following figure (Fig. 12).

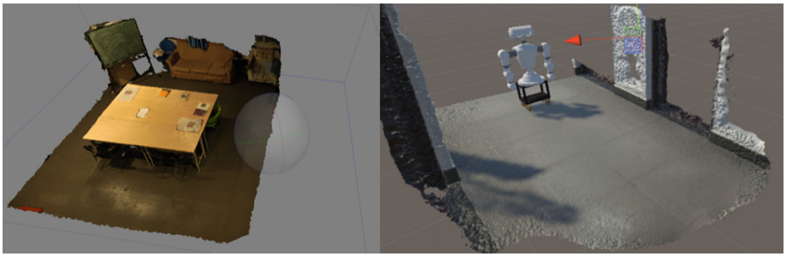


Fig. 12. 3D reconstruction of meeting room and corridor scene

5.2 3D Reconstruction Test Based on Binocular Vision

SFM 3D reconstruction is not good for weak texture scene with few feature points.

According to the characteristics of less lunar terrain environment texture and no obvious prominent features, binocular vision method is used to reconstruct the 3D model, and the model is accurately measured and monitored. Ranging experiment is carried out as following:

(1) A binocular stereo vision system with parallel optical axis is constructed by using two cameras of the same model;
(2) The binocular stereo vision system is calibrated to determine the internal and external parameters of the two cameras;
(3) Use both left and right cameras to shoot the fixed calibration plate scene at the same time (the obtained image pairs are shown in the figure);
(4) In the self-developed human-computer interaction interface, the captured image pairs are imported, while the matching corresponding points in the left and right images are manually selected. Then the 3D coordinate information of the obtained image points in the world coordinate system is calculated by using the principle of triangular ranging.

序号	左x	左y	右x	右y	X	Y	Z
1	768	422	714	448	284.4	200.0	2088.9
2	770	435	716	461	288.9	171.1	2088.9
3	770	450	716	476	288.9	137.8	2088.9

Fig. 13. Human-computer interaction interface and image pair display

In order to effectively verify the accuracy of 3D reconstruction, the gray image of calibration plate is selected for ranging. The actual size of the calibration plate is 30 mm × 30 mm. In order to verify the accuracy of distance measurement, 8 corners in the first row and 6 corners in the first column of the calibration plate are selected, and the absolute and relative error of the measurement distance are obtained (Fig. 13).

Absolute error calculation: $\Delta = (L' - L)/L$, where L' is the measured value and L is the true value;

Relative error calculation: Δ is the absolute error and L is the true value, $\delta = \Delta/L \times 100\%$ (Fig 14).

It can be seen from the data in the table that the reconstructed environment size is basically the same as the real size. With the increase of measurement distance, the absolute error and relative error are reduced, and both arrive below 1%. The best working distance of the camera is within 5m. In the ranging test, it can be seen from the table that there is no significant difference in the y-axis coordinates with the increase of the

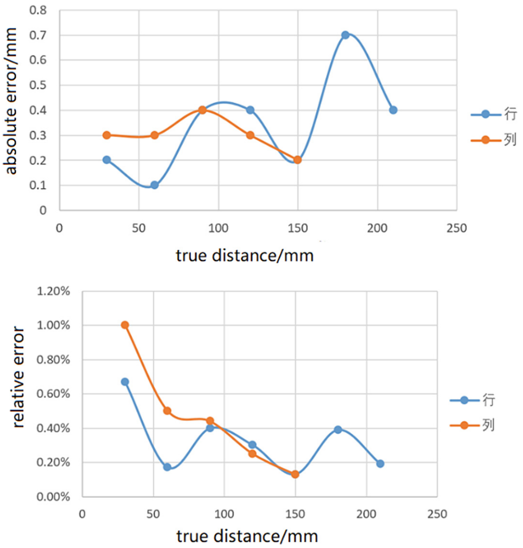
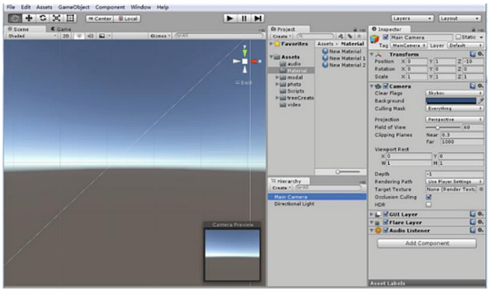


Fig. 14. Absolute and relative error of 3D reconstruction

measurement distance, which indicates that the measured points are at the same height. These verifies the accuracy of the measurement.

5.3 3D Reconstruction Experiment of Typical Lunar Teleoperation Mission

The simulation of virtual scene is based on Unity3D software. Unity3D is a cross platform, fully integrated professional virtual simulation engine that provides rich scene management functions (Fig. 15).

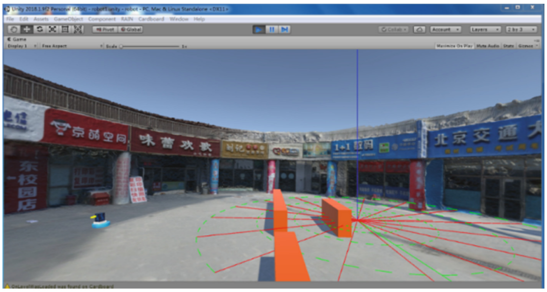


Main Camera
Tag MainCamera Layer Default
Position X 0 Y 1 Z -10
Rotation X 0 Y 0 Z 0
Scale X 1 Y 1 Z 1
Clear Flags Skybox
Culling Mask Everything
Projection Perspective
Field of View 60
Clipping Planes Near 0.3 Far 1000
Viewport Rect X 0 Y 0 W 1 H 1
Depth -1
Rendering Path Use Player Settings
Target Texture None (Render Text
Occlusion Culling ☑
HDR ☐

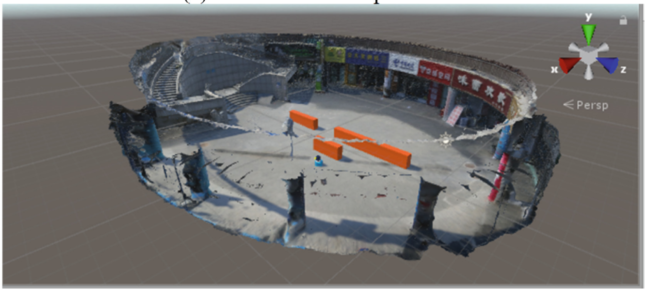
Fig. 15. Unity3D operation interface

Based on a campus environment, 3D reconstruction and robot walking control in virtual reality is simulated (Fig. 16).

The requirement of 3D reconstruction based on Metashape software is very low. Video or even random image sequences can be used for 3D reconstruction. At the same



(a) Scene of robot in position 1



(b) Scene when the robot moves to position 2

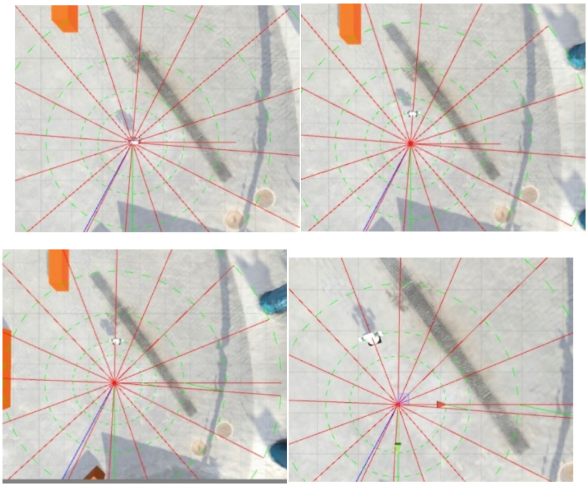
Fig. 16. Description of 3D simulation control based on VR

time, image sequences can be used to realize the self calibration of the camera in the reconstruction process and eliminate the pre-calibration steps of the camera. With the progress of various feature point extraction and matching technology, the robustness of SFM is also very strong. However, the shortage of 3D reconstruction based on software is mainly due to the large amount of computation. Because the reconstruction effect depends on the density of feature points, the reconstruction effect of weak texture scene with fewer feature points is poor.

In order to test the matching accuracy between the size of the environment model in Unity3d and the size in the real scene, the method of walking and rotating the robot is used to verify the accuracy of the model. The matching accuracy of the model has a great impact on the subsequent tests. First, a graph is drawn in OpenGL, which is composed of several concentric circles (green) and rays (red) divergent from the center of the circle. The spacing of several concentric circles is set to a value, and the angle between the rays is set to a value. Then place the robot's walking starting point in the center of the drawing, and verify the dimensional accuracy of the model (Fig. 17).

In OpenGL, we set the radius of the first concentric circle as 2.5m, the radius of the second concentric circle as 5m, and set the angle between several red rays to 30°. Then we add a walking program for the robot in Unity3D. The starting point is the center of the concentric circle, so the robot can move 2.5m and 5m from the starting point respectively. Running the program shows the robot has reached the concentric circle of 2.5m and 5m. Editing the program (let the robot rotate 30° and walk), we can see the robot walking along the rays separated by 30° (Fig. 18).

Fig. 17. Starting point of robot placement



(a) robot starting point (b) robot walking 2.5m (c) Robot walking 5 meters (d) robot rotating 30 °

Fig. 18. Robot walking and rotating control2

With simulation verification, it is proved that the size of the environment model in Unity 3D is consistent with that in the real scene, which lays the foundation for the subsequent experiments.

6 Summary

According to the requirements of 3D environment reconstruction in the future manned lunar exploration teleoperation mission, the structure from motion + binocular vision method was selected, and the 3D reconstruction test is successfully carried out in the laboratory environment. The 3D environment reconstruction and motion control test including robot is successfully realized in the outdoor environment, and the 3D reconstruction accuracy is better than 1%, which can meet the requirements of lunar surface teleoperation for manned lunar exploration.

References

1. Zhang, D., Tian, L., Huang, K.: Jiwu wang Vision tracking algorithm for augmented reality system of telecommunications mobile robots. In: 2020 3rd International Conference on unmanned systems (2020)
2. Wang, J., pei, X.: Distance measurement system based on binocular stereo vision. In: The 2021 International Conference on artificial life and Robotics (icarob2021) (2021)
3. Wang, J., zeng, W.: Research on realization method of augmented reality based on unity3d. J. Robot. Netw. Artistic life **6**, 195 (2019)
4. Shengyi, J., Haifei., L., Song, P., Bo, W., et al.: Design of tele operation ground support system for chang'e-4rover. Spacecraft Eng. **28**(4), 116–124
5. Xin, Z., Aiguo, S., Yonghui, Z., huijun, L.: Design of a virtual human machine system for manipulator tele operation. Manned spaceflight **26**(3), 353–362 (2020)
6. Chang, L., Jianggang, C., Ning, H., et al.: Research on space understanding method in mixed reality for astronaut training. Maned Spaceflight **26**(1), 26–33
7. Huang, Q.: Research on multi modal mixed reality system based on hololens and haptic rendering. Thesis of Nanjing University of Aeronautics and Astronautics, (2019)
8. Xinlei, G.: Mixed reality framework based on visual positioning. Thesis of Xidian University (2019)
9. Xiaoong, X.: Research on Key Technologies of ground tele operation for space robot. Thesis of Southeast University (2017)