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# The Teleoperation Simulation System based on VR

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***Abstract*—Because of the instability and the complexity of the communication between the ground and the space, the teleoperation system faces many problems which can lead to operation failure. In order to enhance the success probability and reduce the unnecessary cost, the predication simulation system based on virtual reality is developed in this paper. The teleoperation command could be done in the system to predict the operating result. The teleoperation command will not be delivered to the real scene except the prediction gets the expected result. And the prediction result could be used to direct the next operation.**

**This paper describes the methods to establish the teleoperation simulation system, and the measures taken to ensure the VR fidelity. The entire system is composed of a virtual scene and a real scene. The teleoperation words on both the real scene and the virtual scene. The teleoperation result in the virtual scene could be used to direct the next operation. A specific algorithm is developed to simulate the time delay between the space and the ground. In the prediction system, timestamp is used to correct the VR scene, special collision detection algorithm is developed to meet the special application environment. A lot of experiments have been done show that the system described in this paper works efficiently and precisely, and be useful to avoid the time delay problem between the space and the ground.**

***Keywords- Teleoperation; VR; Space Robot; Virtual Fixtures***

## I. INTRODUCTION

In recent years, with the rapid development of Chinese space technology, the amount of space operation missions has increased significantly. Since the outer space environment is not suitable for direct human activities, a lot of work has to be done by the space robot. Therefore, along with the scope of application of space robots being expanded continuously, the accuracy and complexity of tasks performed by robots has also been improved. Limited by the existing level of technology, the robots engaged in a variety of space operations that can completely replace human beings in outer space will be unavailable for a good while. Nowadays human-computer interactive cooperation is taken by all countries[1]. The operator on the ground control station controls the robot in space remotely through a video message returned from outer space to accomplish a specific task, and such operational approach is called supervisory control[2]. By using supervisory control, the ground operator and robots in the space working together to complete complex space operations is the main working form for now and the long future.

Since too many uncertain factors existing in outer space environment, improper operation can easily give rise to accidents that resulting in huge losses.

Based on existing experience, there are mainly two difficulties concerning space robot teleoperation[3][4] technology: one is the large time delays caused by data communication process between space and ground, which affect the stability and performance of remote operation seriously; on the other hand, the ground operator can't observe changes in operating environment of outer space in time due to the communication delays, therefore timely and effective manner can't be operated by the space robot.

Without changing of communication technology, signal transmission delay problem of remote outer space operation can't be overcome completely, and only can be resolved to a certain extent through some methods. And for the problem caused by signal transmission delays that the operator can't see the changes in the space environment timely, some advanced methods using virtual prediction techniques is adopted.

Virtual prediction technology has been successfully used in many fields, such as outdoor robot operation, industrial control, space robot operation and so on. Using this technique, the ground operator doesn't operate the robot directly, but operates the virtual robot according to the prediction results of the simulation scenarios, and predicts movement of the real robot to direct next step at the same time. In this way transmission delays can be effectively avoided.

In this paper, we establish a space robot teleoperation simulation system on the ground, and simulate the teleoperation process of space robot and the process of completing outer space task through teleoperation.

## II. SYSTEM FRAMEWORK

In this paper, we simulate the whole space robot teleoperation process, and assist the operator to complete high-precision task by using virtual forecasting technology. We establish network transmission delay module, which we use to simulate data transmission link; and we build three-dimensional virtual reality scenarios of space robot teleoperation scenarios, which can form a control circuit with the ground operator and offset the effect on the system stability and operating characteristics caused by the large communication time delays. The key of this simulation system research is reflected in prediction accuracy, collision detection, teleoperation correction command, model updating and so on.

System framework is shown in figure 1, which consists of ground operating devices, prediction and simulation system and outer space simulation system. The system simulates the real process of space robot teleoperation. The operator issues teleoperation instructions through remote robot operating system, and these instructions are received by the model and used to revise the operation scenarios and prediction and simulation system of the space robot. Prediction and simulation system predicts operation of space robot based on teleoperation instructions, and the virtual scenario display screen will show the prediction results. The operator will continue to issue teleoperation instructions to the space robot based on the prediction results. That cycle repeats, and we don't have to wait for the results showed by the video display screen. After a certain time delay interval, the teleoperation instructions sent by the operator are received by the space robot in the real operation scene, and the real robot will follow the instructions to move, and the real scenario video will be sent to the video display screen.

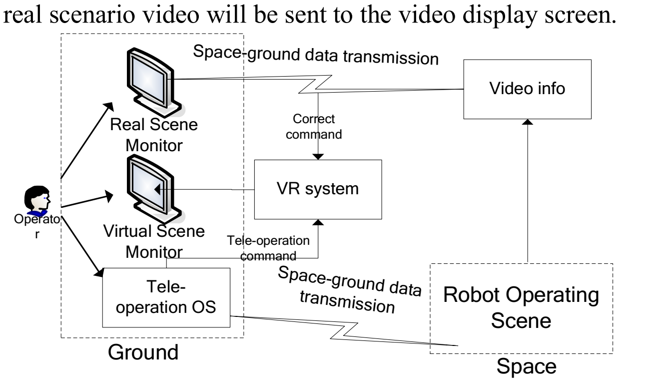


Figure 1. System framework diagram

Ground operation devices consist of teleoperation console, virtual reality display devices and outer space scenario video display equipment. Teleoperation console is used to control the robot in outer space and the robots in virtual reality environment, and its input is enabled by three-dimensional operating handle. The console can control each of multiple degrees of freedom of robots to complete complex operation by using software developed independently. Virtual reality display devices consist of spherical screens and four projectors with a high degree of accuracy, which can send the virtual scenario prediction results back to the operator and form three-dimensional images with information-in-depth and sense of immersion. The video display shows the real scenario video that undergoes time-delay treatment.

We build simulation scenarios just like the space robots entities operation scenarios in the laboratory. We arrange the robot and the related operating devices in a dark room to simulate the outer space operating environment. Many cameras are set in the scenarios to complete multi-angel shooting and send video back to the console; the scenarios also have three-dimensional reconstruction function, and the robots' attitude can be identified through the video sequences. The robot has six degrees of freedom, and is light weight and with flexible movement.

We must transmit information and video between ground teleoperation console and the space robot operation scenarios. To simulate real time delays in the space-ground communication, our system simulates space-ground communication transmission link, and generates large time delays arising from space-ground communications. Every time delay lasts for about 1-3 seconds, and all the time delays are normally distributed. Time delays over a period of time are shown in figure 2, and the delay probability distribution is shown in figure 3. Because the world communication transmission process forms a loop, so during the whole transmission process the time delay can last for 3-7 seconds.

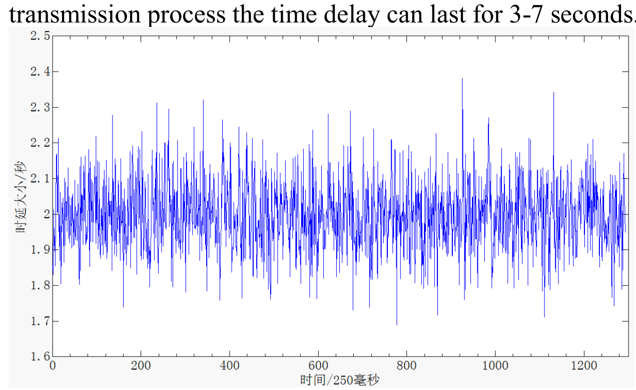


Figure 2. Time delays over a period of time

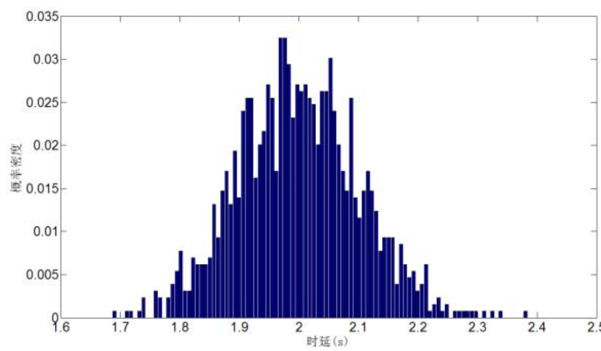


Figure 3. Time delay probability distribution

Prediction and simulation system is core of the whole simulation system, and we build virtual space robot operation scenarios totally the same as the real ones in the ratio of 1:1. So that based on instructions sent from ground operating devices we can operate virtual outer space operation scenarios by using virtual reality technology, and then predict the real robots operating scenario condition, and output simulation results to the virtual scenario display to guide the operator's next step. In this way the operator can evade large time delays arising from space-ground communication transmission, and complete the remote control to space robot coherently. Because virtual scenarios can't be the same as the real scenarios, and the system is subjected to three-dimensional modeling accuracy, outside forces and other uncontrollable factors, so errors will be generated during the prediction simulation process, and these errors are accumulated in the continuous running process and will lead to mistakes. In order to reduce large simulation errors, at regular intervals, our simulation system will use the robot status information from the real scenario video information to modify the behavior of robot in virtual scenarios, so that we can keep errors within controllable range

## III. Space Robot Kinematic Model

Virtual reality system is core of simulation and prediction system, and match degree between virtual scenarios and real scenarios can directly determine accuracy of the prediction. Only the match degree is high enough, could our prediction results be accurate.

We use real-time visualization three-dimensional modeling software Multigen Creator developed by Multigen Paradigm as virtual scenarios modeling tool, and OSG(OpenSceneGraph) as model driven. OSG is an open source graphics library and is developed by OpenGL technology, and it also has open source and platform independence. R120 robot created by IBB company gives us model to use when we create space robot, ant the three-dimensional model is shown in figure 4.

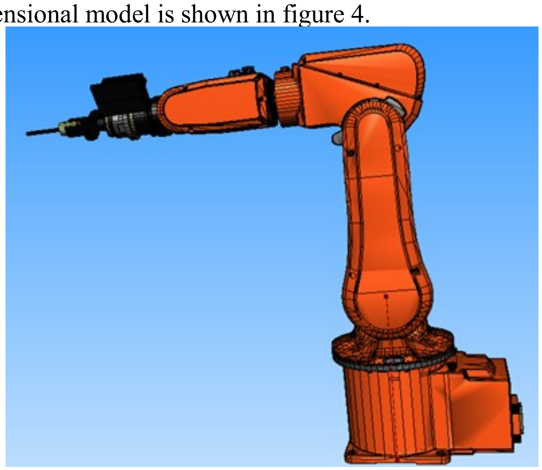

Figure 4. model of the space robot

Space operation task of the prediction and simulation system is to control the probe in the robot's head through teleoperation technology so that the probe can pass through the tunnel and keep close to the bottom of the tunnel without collisions with any wall of the tunnel. The top view of the tunnel is shown in figure 5, because there are certain changes in the horizontal and vertical directions, so we need to take both horizontal and vertical displacement into account during the motor process of the robot, which means we have to control operation process precisely.

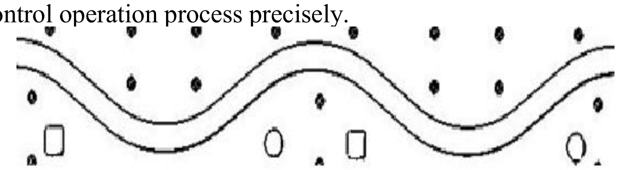

Figure 5. Top view of the tunnel

The space robot has six degrees of freedom, and moves by connecting rods, and it can be adapted to many kinematic models[5]. Because the shape of terminal probe is single, so we choose DH model. Since each degree of freedom revolves around a specific axis, so we choose rotation axis as Z axis, and each moving coordinate system of degrees of freedom is shown in figure 6.

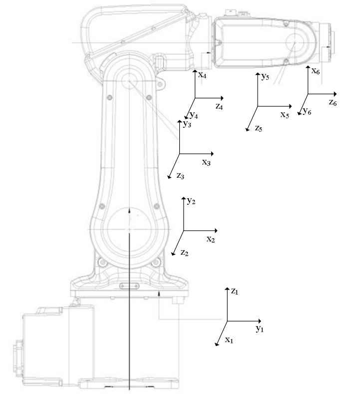


Figure 6. coordinate systems

We can calculate kinematics model of the robot based on the connection rods coordinate systems. Transformation of connecting rods coordinate system {i} relative to connecting rods coordinate system {i-1} is represented as .Based on D-H algorithm, we can have

$$ {}^{i-1}_{i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & \alpha_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -d_i \sin\alpha_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i \cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Transformation matrix of position of the robot's terminal relative to the foundation bed coordinate system is:

$$ {}^{0}_{6}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T\,{}^{5}_{6}T \quad (2) $$

We can calculate the position of the robot's terminal relative to the origin of foundation coordinate system through the equations above.

## IV. Collision Detection

It is a very delicate and tough task to control the robot to move and keep close to the bottom of the tunnel without collision with the bottom or the sides of the tunnel through teleoperation technology, but we can complete this task by using virtual fixture technology[6].

In the virtual environment, we set a virtual fixture on the probe of the robot's terminal, and the fixture is little bigger than the diameter of the probe as shown is figure 7. When the robot is moving we can use the virtual fixture to detect collisions of the probe with the tunnel. Because the virtual fixture is bigger than the probe, so when the virtual fixture collide with the tunnel, the probe is close the tunnel wall but doesn't collide with the tunnel walls. The robot can use that position as a reference and stay suspension and move along the tunnel to complete the teleoperation task.

Collision detection is the key technology and decides whether the operation task can be completed smoothly or not, which means our collision detection must be fast and accurate.

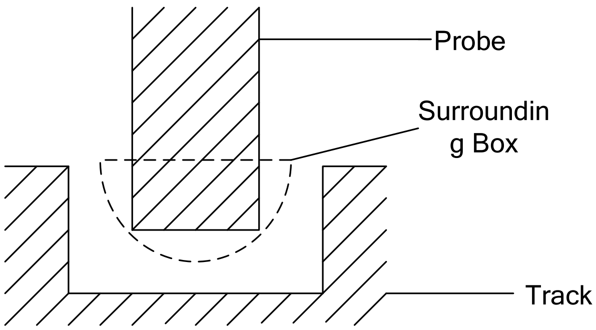


Figure 7. the probe virtual fixture

OSG provides us with bounding volume collision detection algorithm. But because of the irregularity of the tunnel, the collision detection efficiency is low and inaccurate. After a lot of experiments, according to the characteristics of teleoperation task and the vertical side walls and change of height of the bottom of the tunnel, we develop nine-point collision detection algorithm to meet the requirements. The algorithm select nine collision detection points on the hemisphere virtual fixture as shown in figure 8. According to the collision condition of the only nine points with the tunnel during the running process, we can reduce computing complexity greatly and improve the efficiency of collision detection and the response speed, which makes the operation easy for the operator.

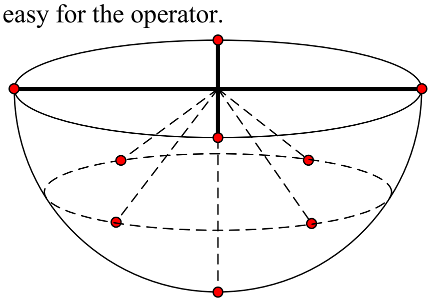

Figure 8. Nine-point collision detection algorithm

Nine-point collision detection algorithm is fast and highly sensitive. As is shown in figure 9, the algorithm provided by OSG can detect collision, and nine-point collision detection algorithm can detect the critical state of collision.

## V. TELEOPERATION CORRECTION COMMAND

In the real scenarios, the primary task is to ensure that the robot has no collision with the tunnel to avoid hardware damage. So we need to correct the teleoperation command. Because the probe is surrounded by the virtual fixture completely, when the virtual fixture collides with the tunnel in the virtual scenarios, the probe is going to collide with the tunnel in the current movement trend. At the moment we need to stop the command of moving towards the collision direction and correct the teleoperation command to avoid the collision of the robot with the tunnel in the real scenarios. By detecting the positions of the collision points, we can predict he movement trend of the probe and provide data for correction command.

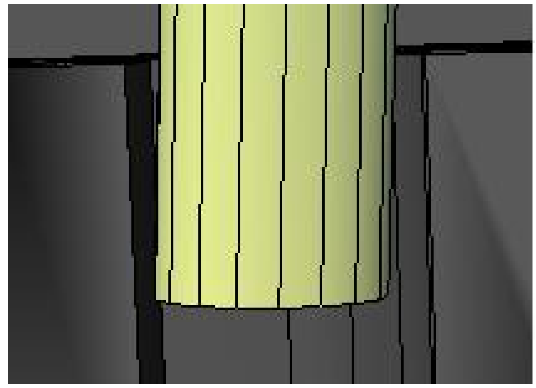

Figure 9. Collision situation

## VI. CORRECTION OF SIMULATION SCENARIOS

Virtual reality scenarios are different from the real scenarios in the movement environment respect. The movement condition of virtual reality scenarios is ideal, which means the robot can follow the teleoperation instructions to move and avoid influence of various external forces. The real scenarios are affected by gravity and friction, and the precision of the mechanical device is also a problem, so it’s hard to ensure the simulation results are the same with the real scenarios when we are simulating the real scenarios. Each operation can cause errors. With increase of the amount of operating instructions, the errors will be magnified and lead to big difference between the virtual scenarios and the real scenarios, which will result in mistakes in simulation.

To avoid the situation, our system adopts virtual scenario correcting strategies, which means we use the attitude of the robot in the real scenarios to modify the attitude of the robot in the virtual scenarios.

There are two approaches to compare the attitude of the robots:

(1)Obtain the parameters of the degrees of freedom of the real robot by sensors, and then compare them with the parameters of the robot in virtual scenarios. This approach is accurate and size of data transferred is small, so the process is easy to automatic control.

(2)Adjust the positions and directions of the cameras in virtual scenarios to be the same as the real scenarios, and then fuse the images of the virtual robot with the ones from real video to find attitude difference through contact ratio. By this approach we can intuitively see the inconsistence of attitude, but it’s not accurate enough and size of data transferred is large, so this approach is not suitable for world transmission. In addition, for the problem of adjusting the cameras to make them consistent, without human intervention, the task needs great amount of calculation and operation time to complete, so the process is not easy to automatic control.

In order to improve system run speed, we choose the first approach to match attitude. The attitude of R120 robot can be provided by the attitude sensors. But because of space-ground communication time delays and sizes of delays keep changing, we can’t be sure the attitude obtained from the real scenario video is at what point, which means we can't match attitude. To solve this problem, our system adopts time-stamp strategy, which means the teleoperation instructions sent from the ground to space robot are time stamped. After the robot executes the instructions, the attitude information will be sent back to the ground console with the same timestamps. In this way we can be sure the robot attitude information after each instruction is executed.

(a) real scene (b) virtual scene

Figure 10. System running effect

When operator is operating the robot remotely, virtual scenarios will do the prediction and simulation based on teleoperation instructions as shown in figure 10. When operator stops operation for a period of time, our system will retrieve timestamp of the last teleoperation instruction automatically and extract the corresponding robot attitude information from the information sequences sent from the real scenarios to correct attitude of virtual robot. In this way virtual scenarios and real scenarios can maintain a high level of consistency, and the system can eliminate errors extremely. So when the ground operator begins a series of operation, initial state of virtual scenarios can match with the real scenarios state precisely, then we can ensure the prediction and simulation is reliable.

Table 1 and table 2 show the spatial data of probe terminal of real robot and virtual robot after ground operator operate continuously for one minute following the same steps. We choose three sets of data.

TABLE I. UNCORRECTED PROBE POSITION DATA

| N | Virtual robot | | | Real robot | | | dista |
|---|---|---|---|---|---|---|---|
| o. | x | y | z | x | y | z | nce |
| 1 | -5.07 | 21.49 | 2.51 | -5.07 | 21.48 | 2.49 | 0.01 |
| 2 | -5.16 | 21.49 | 3.29 | -5.20 | 21.52 | 3.25 | 0.06 |
| 3 | -5.53 | 21.40 | 1.78 | -5.63 | 21.37 | 1.62 | 0.19 |

TABLE II. CORRECTED PROBE POSITION DATA

| N | Virtual robot | | | Real robot | | | distanc |
|---|---|---|---|---|---|---|---|
| o. | x | y | | x | y | z | e |
| 1 | -5.06 | 21.48 | 2.50 | -5.06 | 21.51 | 2.49 | 0.03 |
| 2 | -5.17 | 21.50 | 2.30 | -5.18 | 21.48 | 2.31 | 0.02 |
| 3 | -5.53 | 21.79 | 1.78 | -5.51 | 21.81 | 1.77 | 0.03 |

From the experimental data we can see during the teleoperation process the difference of probe position between real robot and virtual robot will become bigger and bigger if we don't correct position, which will lead to intolerable mismatch and mistake of teleoperation; but after position correction position deviation between real robot and virtual robot doesn't exceed units of 0.04, and this precision can ensure teleoperation completed smoothly.

## VII. CONCLUSION

In this paper, we build the space robot teleoperation prediction and simulation system, which enables ground operator to operate remote real scenario based on prediction of the three-dimensional virtual reality simulation scenarios with big world communication time delays, and we also simulate the whole process of delicate work. Experiments show that the prediction and simulation system is stable, real and effective, and is meaningful for operator training and teleoperation technology research. Methods proposed by this paper are versatile and can be extended to any robot and any scenario, and also can be applied to environmental disasters, nuclear environment, deep sea and other environment humans can't work on-site.

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