The Ground-based Validation Technology of Teleoperation for Space Robot

Xueqian Wang
Division of Control and Mechatronics Engineering
Harbin Institute of Technology Shenzhen Graduate School
Shenzhen, Guangdong Province, China
xqwang@robotsat.com

Bin Liang, Cheng Li and Wenfu Xu
The Institute of Space Intelligent System
Harbin Institute of Technology
Harbin, Heilongjiang Province, China
{bliang, cli, wfxu}@robotsat.com

***Abstract*—This paper addresses a ground-based validation subsystem which verifies the functions and performance of the teleoperation system for space robot. The subsystem is comprised of three modules: the physics verification module, the onboard verification module and the communication simulator module. In the physics verification module, a hybrid experiment concept which combines the mathematical model with the physical model is used. The key issues of the physics verification module are dynamic emulation and kinematic equivalence, in which the behaviors of the space robotic system are calculated by its dynamic equations. The motion of its end-effector and the space target is realized by two industrial robots. The concept of hardware-in-the-loop simulation is used in the onboard verification module to verify the onboard computer's processing ability. The communication simulator can provide fidelity communication conditions which consist of time delays and communication bandwidth. Lastly, a teleoperation system is set up, and many experiments have been done on the system. The experiments verified the effectiveness of the work in the paper.**

Keywords—Space Robot, Teleoperation, Ground-based Validation, Kinematics equivalence, Time Dalay

I. INTRODUCTION

Free-flying space robot systems, in which robotic manipulators are mounted on a free-flying spacecraft, are envisioned for assembling, maintenance, repair, and contingency operations in space. Generally speaking, fully autonomy of space robot is considered as an impossible goal in the near future from the eighties of the 20th century because of the restriction of mechanism, control, sensor and artificial intelligence. So the research emphasis is to build a local autonomous space robot system with operator's assistance [1].

Almost all the launched space robots can be teleoperated from the ground. ROTEX (Robot Technology EXperiment) is the first remotely controlled robot in space. It demonstrated the experiment of grasping target under teleoperation from ground [2]. ETS-VII (Engineering Test Satellite No.7) is the first free-flying space robot system. Its purpose is to study the rendezvous and docking (RVD), and space robotic (RBT) technologies. The space robot was successfully teleoperated from the ground even large time delay existed [3,4]. GETEX (German ETS-VII Experiment) is a high-level task-oriented robot programming system, which is characterized as learning by showing in a virtual environment. The system includes all the sensor-based control features already tested in ROTEX, but in addition provides the feasibility to program a robot system at an implicit, task-directed level [5,6].ROKVISS(Robot Komponent Verification on ISS) has two main goals which are the demonstration and verification of light-weight robotics components, under realistic mission conditions, as well as the verification of direct telemanipulation to show the feasibility of applying teleprensence methods for future satellite servicing tasks [7,8]. Space teleoperation will play an important role in unmanned on-orbit servicing (OOS). Teleoperation has several serious difficulties: communication time delay, restrictions of communication capacity, limitations of onboard computation ability etc. In addition, the space robot systems require a high level of safety and reliability since a mis-operation may induce serious damages. So teleoperation system must be verified before the space robot launched to ensure security and feasibility of operations.

NASAD (now JXAX, Japan Aerospace Exploration Agency) developed a space robot test-bed to evaluate the teleoperation system form ETS-VII. The test-bed was composed of a simulated satellite mounted robot system, a simulated on-ground robot control station, and a simulated space communication link [9]. German Aerospace Center (DLR) has built a realistic hardware-simulation as built up in the lab with two robots. One robot is supporting a satellite model with apogee motor realizing arbitrary kinds of tumbling motions, while the other robot holds the capture tool and tries to servo and finally dive into the apogee motor [10]. Canadian Space Agency (CSA) has developed STVF (SPDM Task Verification Facility) to verify the contact dynamic performance of the Special Purpose Dexterous Manipulator (SPDM) [11,12]. A ground-based experimental system is built up which combines the mathematical model with the physical model for the verification of the planning and control algorithms of space robotic system [13].

In this paper a ground-based validation subsystem, an important part of the teleoperation system, was designed and built up. The subsystem has three main functions: telemetry data generation, image data generation of hand eye camera and global camera, transmitting channel simulation. Using the subsystem, the entire teleoperation system can be validated and evaluated.

The paper is organized as follows: Section II introduces the space robotic system and its teleoperation system. And the ground validation subsystem is introduced in Section III. Then, Section IV gives some experimental results. The last Section is the conclusion and discussion.

II. Space Robot and Its Teleoperation System

A. *Space robot system*

The space free-flying (SFFR) robotic system studied in the paper is composed of a satellite and a 6DOF manipulator mounted on it. And a target satellite is considered as a object to manipulate. SFFR consists of a spacecraft base and a 6 DOF manipulator on the base, as Figure 1. The body frames of the manipulator are defined by Denavit-Hartenberg convention, as Figure 2. The base frame, which is fixed on the satellite, and the ith body frame are represented by $\sum_B$ and $\sum_I$ respectively. The Denavit-Hartenberg parameters of the manipulator are given in TABLE I.

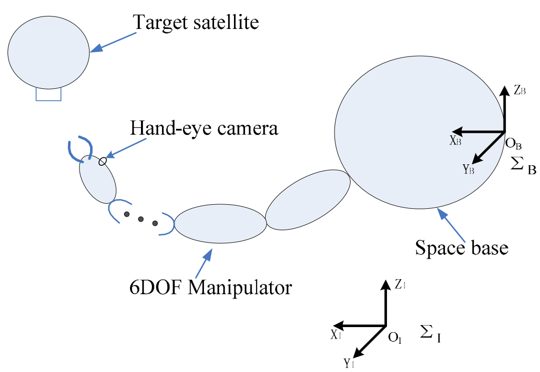


Figure 1 The space robot system

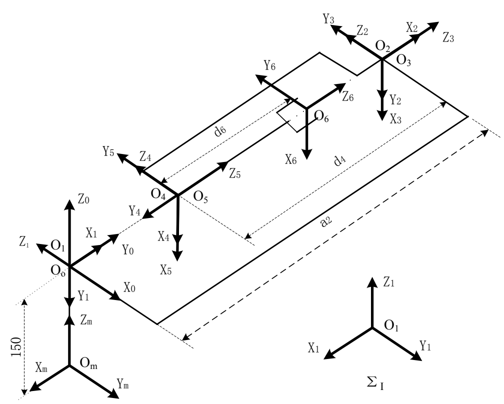


Figure 2 D-H coordinates of space manipulator

TABLE I. PARAMETERS TABLE OF SPACE MANIPULATOR

linki	θi	αi	ai （mm）	di （mm）
1	90°	-90°	0	0
2	-180°	0	680	0
3	-90°	90°	0	0
4	0	-90°	0	-580
5	180°	90°	0	0
6	0	0	0	225

B. *The Teleoperation System of Space Robot*

The teleoperation system consists of predictive simulation subsystem (PSS), master-slave control subsystem (MSCS), task planning subsystem (TPS), information processing subsystem (IPS) and ground-based validation subsystem (GVS), as Figure 3.

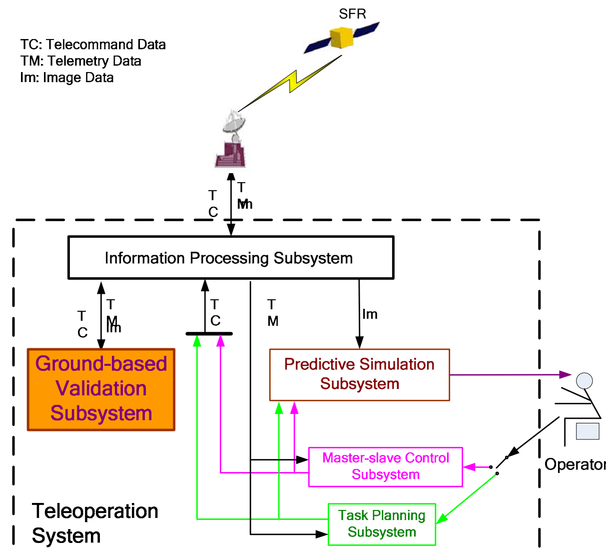


Figure 3 Composition of the teleoperation system

The functions of each subsystem are as follows:

- PSS is designed to predictive the state of SFFR on-line or to simulate the telecommand off-line. It can also detect the collision and give the warning information.
- The main function of MSCS is to generate the telecommand data by master manipulator and provide feedback force.
- The TPS is used to analyze, decompose and make decision and generate the motion data aiming at different teleoperation task.
- IPS is the interface between the teleoperation system and the teleoperation support system and provides the functions of data processing command safety checking and network communication.
- GVS can verify the teleoperation on-line. It can also be used as the teleoperated target of other subsystems.

III. The Design of Ground-based Validation Subsystem

A. *The Configuration of the subsystem*

Figure 4 is an illustration of the GVS (Ground-based Validation Subsystem), which is composed of physics verification module, onboard verification module and earth to orbit communication simulator module. Figure 5 shows physical interfaces between each device of GVS.

Physics verification module can verify the end-effector motion with two industry robot based on the concept of dynamic emulation and kinematic equivalence. This module consists of two industry robots and their control computer, two hand-eye cameras, a global camera and the vision computer. Hand-eye cameras verify the target measuring algorithm and the global camera provides the global vision of the environment.

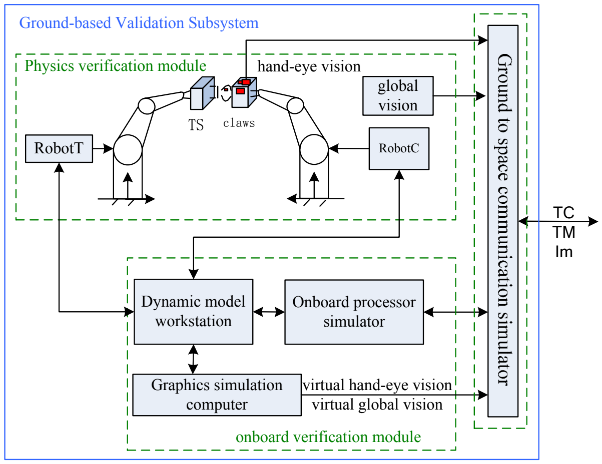


Figure 4 Composition of the ground-based validation subsystem

Onboard verification module verifies the capability of the onboard computer to assure that the command can be executed successfully. This module is composed of dynamic model workstation, graphics simulation computer and onboard processor simulator.

In the onboard verification module, the onboard verification model which has the same electric interface as the real space robot is the fidelity simulator of the space robot system.

Ground to space communication simulator module providing the time delay and bandwidth simulation of communication channel. It consists of two computers.

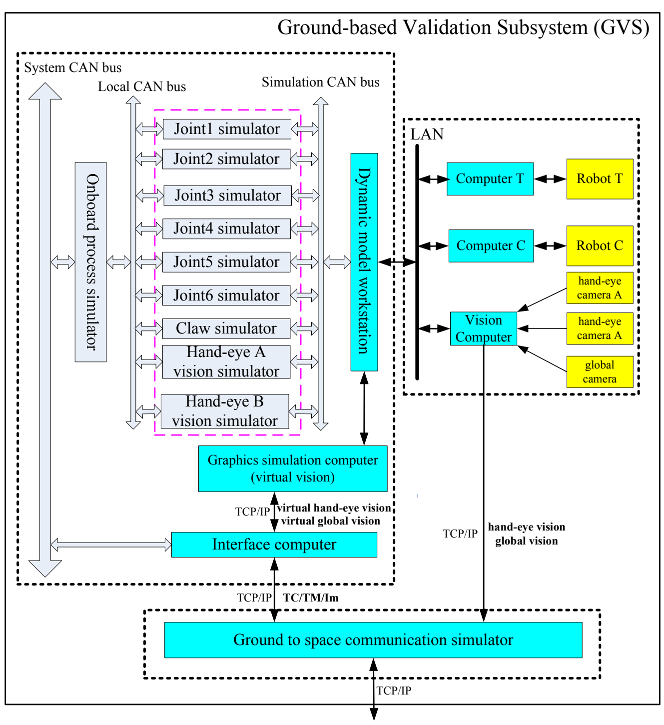


Figure 5 Physical interfaces of GVS

B. *The Physics verification module*

Figure 6 shows two possible laboratory concepts for simulation. In a, Robot A' base is mounted on Robot B's end-effector and its motion is computed using the equations of free-flying robot. The target is mounted on Robot T's end-effector. In b, Robot A's base is fixed on the floor and its motion is computed using the equation of free-flying robot also. But Robot T's motion is computed relative to Robot A's base. Compared with a, b can be realized relatively simply. So we design the experimental system on the concept b.

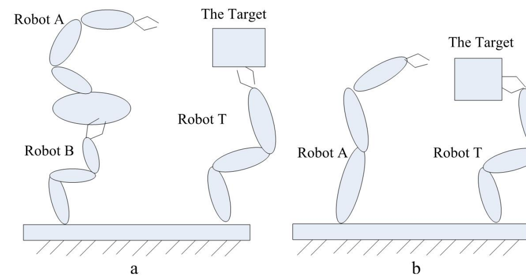


Figure 6 A schematic description of two simulation concepts

There are two important concepts: dynamic emulation and kinematic equivalence. Dynamic emulation means that the behaviors of the whole space system, including space manipulator, its base and the target, are emulated by the precise dynamic equations. Kinematic equivalence means that the end-effector motion of the lab robot equals that of the space manipulator, i.e. the end-effector's motion of the space manipulator is realized by the lab robot.

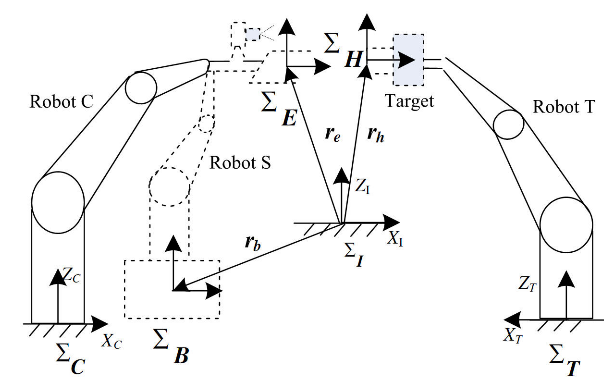


Figure 7 Kinematic equivalence mode I

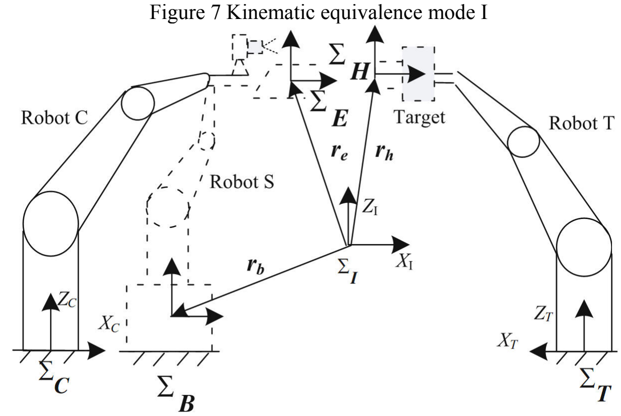


Figure 8 Kinematic equivalence mode II

Figure 7 and Figure 8 show two modes of kinematic equivalence. In the first mode, the bases of Robot C and Robot T are assumed to be fixed in the inertial frame. In the laboratory environment, Robot S's end-effector coincides with Robot C's end-effector. In the second mode, Robot S's base is fixed in the inertial frame also. That is to say, Robot T implements the motion of space base. The realizations of the two modes are shown in Figure 9 and Figure 10 respectively. For the detail content, see [13]. Onboard processor schedules the task when it receives commands, and then controls the manipulator.

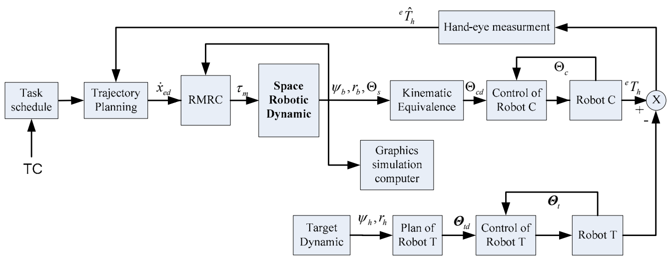


Figure 9 Dynamic emulation and kinematic equivalence of mode I

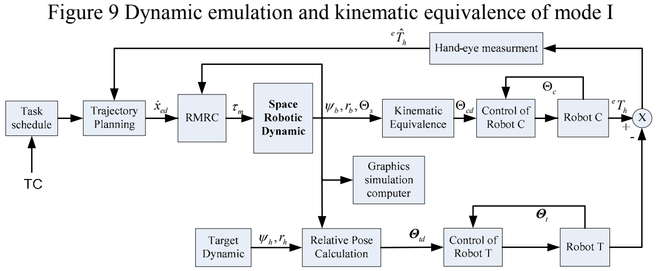


Figure 10 Dynamic emulation and kinematic equivalence of mode II

C. *The Onboard verification module*

In the onboard verification module, the onboard computer and its physical interfaces are coincides with the real parts. Dynamic of the whole space robot system which contains space base and the manipulator is run in the dynamic model workstation. Hand-eye vision and global vision should be provided to the operator when GVS is the operational objective for the other subsystems of teleoperation system off-line. Graphics simulation computer generates the virtual vision image by the virtual camera in the three dimensional graphics. In this paper, we use the program language Java and its 3D graphics library Java3D.

D. *The Communication simulator*

Communication link between the teleoperation system and SFFR consists of network link on ground and wireless link of ground to space. Its conditions include time delays, jitter, bandwidth limitation, blackout and routing of commands and telemetry [14,15]. The time delays contain processing time delay and transmission time delay. The bandwidth is mainly limited by radio link.

1) *The simulation of time delays*

The generation of communication time delays between the master and slave is an important function of the channel simulator. Constant and varying time delays can be provided.

In the case of constant time delay, the time delay from the master to slave (up-link time delay) as well as the time delay from the master to the slave (down-link time delay), must be multiple of the simulation period (δT). A buffer which size is obtained from the time delays is created, as Figure 11. The procedure is shown as follows:

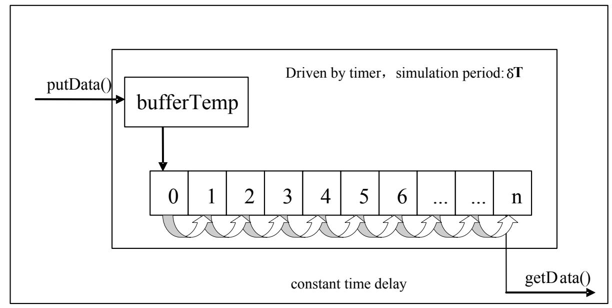


Figure 11 Constant time delay

a) Store the command in bufferTemp.

b) Store the command of bufferTemp in buffer, and move every command backward one unit.

c) Get the command from the final unit if it is not zero Where the buffer units are initialized to zero and this method is executer once in each timer step.

In the case of varying time delays, the loop buffer is used, as Figure 12. The random delays are the result of data transfer delays, and processing delays in the system. To generate random delays, the maximum time delay must be specified. A function provides the random numbers which are produced by the time delay regulation, and it is used as the parameter of the timer. Two threads are used, input thread and output thread. The procedure is shown as follows:

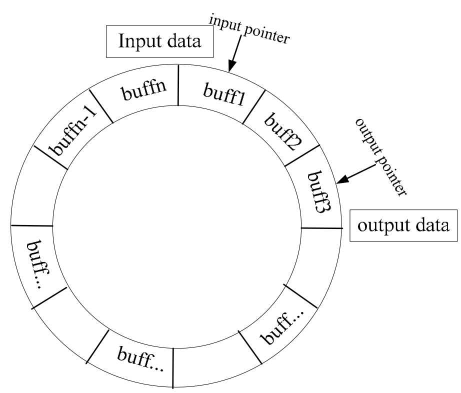


Figure 12 Varying time delay

a) Store the command in the unit which is pointed by the input pointer.

b) Set the time delay value which is a random number.

c) Get the command of the unit which is pointed by the output pointer.

Where the pointer of input and output point the first unit, and the buffer units are initialized to zero also.

2) *The simulation of the communication bandwidth*

Communication bandwidth is limited in the radio link but the network link's is large enough, so the bandwidth simulation of radio link is needed. Bandwidth is simulated using the serial bus RS-232 which can provide stable transmission rate by setting the baud rate. The Microsoft Communications Control provided by Microsoft has been used for serial communication.

IV. Experimental Application

The teleoperation system has been setup in our laboratory, as Figure 13. With the teleoperation system, some experiments have been done to verify the teleoperation technology. In this paper, two typical experiments are described here [16].

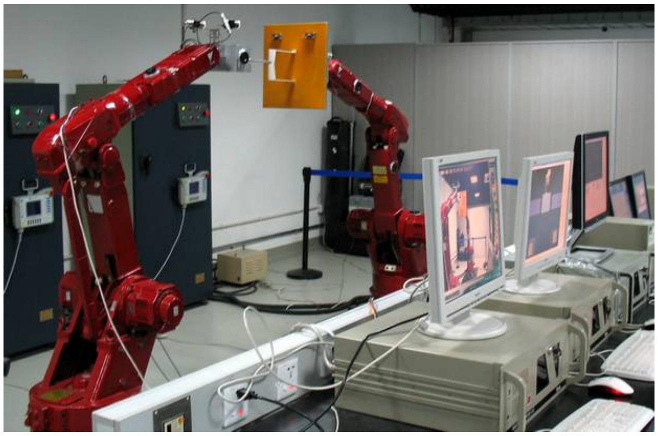


Figure 13 The teleoperation system

A. Experimental conditions

Attitude control accuracy of SFFR is 0.5°/s, and attitude stability is 0.05°/s. Two specific poses are set, the capture preparing pose (CPP) and the nominal berth pose (NBP), definition as follows.

1) Capture preparing pose.

CPP is the pose where the target satellite is captured. The pose of the end-effector frame in the base frame is [1920 mm， -9.52 mm， 493.50 mm， 0°， 0°， 180°], and the corresponding joint angle is that $[\theta_1, \theta_2, \cdots, \theta_6] = [0.00^o, -132.28^o, 86.90^o, 0.00^o, 136.28^o, 0.00^o]$ (fold state).

2) Nominal Berthing pose

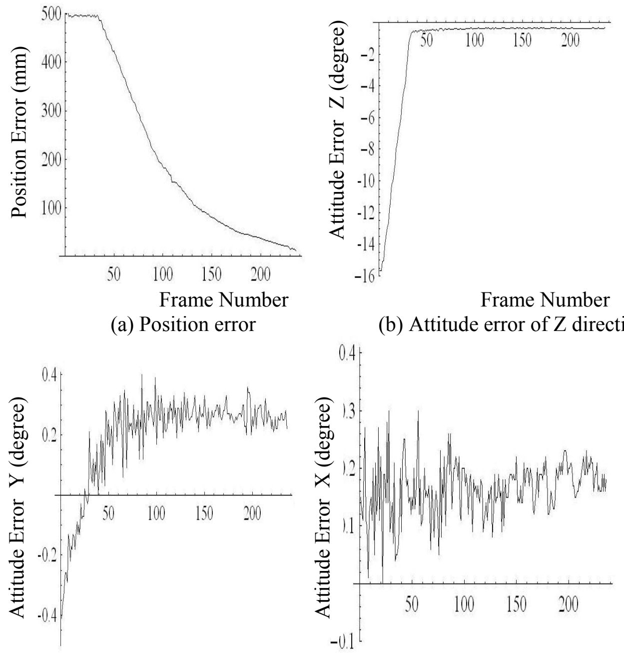
NBP is the pose where the end-effector frame in the base frame is [1920 mm，-9.52 mm，193.50 mm，0°，0°，180°], and the corresponding joint angle is that $[\theta_1, \theta_2, \cdots, \theta_6] = [0.00^o, -132.28^o, 86.90^o, 0.00^o, 136.28^o, 0.00^o]$ (fold state).

Target satellite can be considered as captured when the end-effector frame and the handle frame coincide with each other. Two typical experimental results are shown as follows.

B. Experimental Results

1) Capture experiment in the master-slave teleoperation mode

The target capture experiment with commands generated by MSCS has been done and the experimental results are shown, as Figure 14. (a) is the position error which is the distance between the end-effector frame and the handle frame. (b), (c) and (d) are attitude errors expressed in Euler angle. In the experiment, the pose of the end-effector is adjusted in the preceding fifty frames and the velocity decreases with the distance smaller.



(a) Position error (b) Attitude error of Z direction

(c) Attitude error of Y direction (d) Attitude error of X direction

Figure 14 Capture experimental results in the master-slave teleoperation

2) Capture experiment in share teleoperation mode

As the former experiment, this experiment is done in the share teleoperation mode. The autonomous trajectory planning and visual servoing control algorithm is used when the end-effector is approach to the target. The results are shown, as Figure 15.

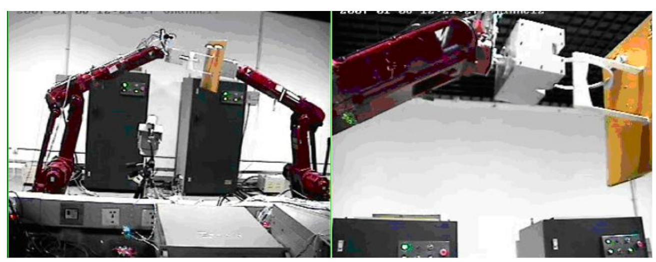


Figure 15 Capture experimental results in the share teleoperation mode

V. Discussion and Conclusion

In this paper, the hybrid experiment concept and the hardware-in-the-loop concept are used and a ground-based validation subsystem is set up. The subsystem has advantages as follows:

- Physics verification and onboard verification are both done: which can verify the operation more completely.
- Virtual camera image which is fidelity to the real image.
- Both of the constant and varying time delays are simulated.
- It can be extended to validate other teleoperation systems by small modification.

However, there is a shortcoming of the system which is that the workspace of Robot C does not equal that of the space manipulator. That is to say, if the whole workspace of the space manipulator needs covering, the dimension of the industrial robot must be larger than that of the space robot. Fortunately, the influence is very small.

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