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Force Reflection and Manipulation for a VR-based Telerobotic System

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ABSTRACT

This paper reports the use of virtual reality (VR) and force reflection in a telerobotic system developed in our laboratory. Robots governed by remote human operators are excellent candidates for work in hazardous or uncertain environments, such as nuclear plants or outer space. However, enabling the operator to feel physically present at the remote site and to sense what the robot touches are challenges to overcome. Recent gains in the capabilities and popularity of virtual reality used to generate realistic telepresence allowed us to develop a telerobotic system in a virtual environment. We also equipped the system with force-reflection capability needed to tackle tasks requiring refinement and responsiveness. To evaluate the effects of the virtual reality and force-reflection techniques on teleoperation, we designed a series of experiments, in which these techniques were applied to tasks involving force manipulation.

Key Words: force reflection, force manipulation, virtual reality, telerobot

I. Introduction

Teleoperation technologies have been applied in hazardous or uncertain environments, such as nuclear plants, outer space, or deep oceans, and also to highly automated systems that are not necessarily hazardous but which demand human intervention for monitoring and detection of abnormalities, such as in aviation (Mitsuishi *et al*., 1994; Sheridan, 1992; Tachi, 1998). These technologies make it possible for operators to enter remote environments with scales or physical laws much different from those in the normal human world. Successful implementation of teleoperation systems demands the creation of environments that make the operator feel as if she or he is actually present at the remote site. In addition, proper information from the remote sites needs to be transmitted back to the operator via various sensing devices, such as vision, position, and force sensors. This paper reports on a telerobotic system developed in our laboratory which uses virtual reality (VR) to generate more realistic telepresence, and which is equipped with a force-reflection capability to help the operator feel remote objects.

In recent years, virtual reality has gained much popularity and has been applied in various fields, such as entertainment, education, training, and industry (Boman, 1995; Burdea and Coiffet, 1994; Göbel, 1996). A general definition of virtual reality is that it is a simulation in which computer graphics are used to create a realistic-looking world. In practice, a simulation is usually three-dimensional (3D), dynamic, and interactive. Further bringing in multi-media techniques enables virtual reality to go beyond pure graphics in emulating reality. And with the inclusion of visual and haptic interfaces, such as head mounted displays (HMD), data gloves, and force-reflection joysticks, operators can visualize, manipulate, and interact with objects in the virtual world more naturally (Burdea, 1996; Goto *et al*., 1995; Minsky *et al*., 1990; Yokoi *et al*., 1994; Yokokohji *et al*., 1996; Yoshikawa *et al*., 1995). These appealing features of virtual reality make it an excellent candidate for generating realistic, virtual environments for the proposed telerobotic system.

The sensation of touch can help the operator deal with tasks that demand delicacy and compliance, as in assembly or handling fragile objects. Force sensors are,

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thus, needed and are mounted on the robot manipulator to reflect contact forces induced when the human operator interacts with remote objects. In addition, we have also incorporated into the proposed telerobotic system a joystick equipped with force-reflection capability (Kazerooni and Her, 1994; Salcudean *et al*., 1995). With such a joystick, the contact forces can be transmitted to the human operator's hand directly, letting the human operator actually feel the forces the real robot manipulator senses. Force-reflection strategies are employed to assist the operator in force manipulation and to tackle problems usually encountered in teleoperation, such as time delay (Anderson and Spong, 1989; Kim *et al*., 1992). In the rest of this paper, the proposed VR-based telerobotic system is described in Sec. II. Force-reflection strategies are discussed in Sec. III. Sec. IV presents a series of experiments for evaluating the effects of virtual reality and force-reflection techniques on teleoperation performance. Conclusions are given in Sec. V.

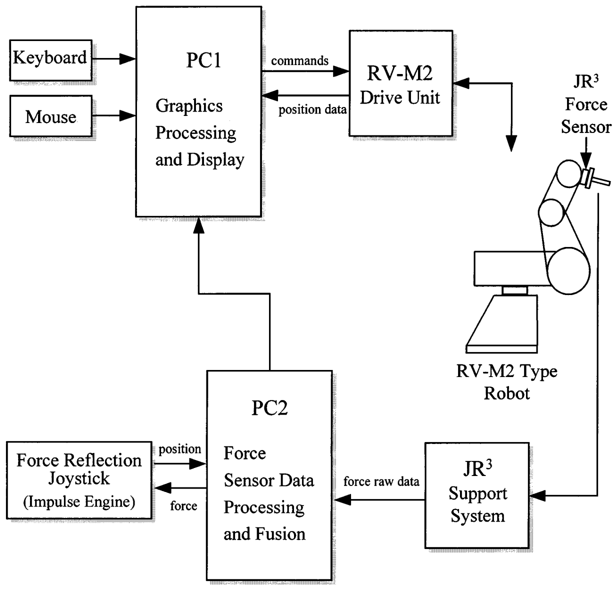

Fig. 2. System organization of the proposed VR-based telerobotic system.

II. Proposed VR-based Telerobotic System

Figure 1 shows the block diagram of a general VR-based telerobotic system. The system consists of VR I/O devices and a VR engine in the virtual side, and a robot and sensors in the real world. The VR I/O devices provide human-computer interaction in the system. Through these devices, the operator inputs commands into the computer and receives feedback, such as visual, auditory, and haptic feedback, that yields the feeling of immersion. The VR engine can be viewed as the simulation manager in a VR-based telerobotic system. It formulates the virtual environment, renders the scene, and manages object behaviors in the simulation loop while processing sensor data from the real world and sending commands to the robot manipulator. A successful implementation of the VR engine has a significant impact on the performance of the telerobotic system by providing a more realistic modeling of the real world and better communication between the virtual and real worlds. The robot is located on the remote side of the telerobotic system. Thus, sensors, such as position and force sensors, are needed to provide information about the situation at the remote site. The robot receives commands from the operator via the drive unit, and sensor data are sent to the VR engine via an intermediate transmission line, both of which may induce transmission time delay.

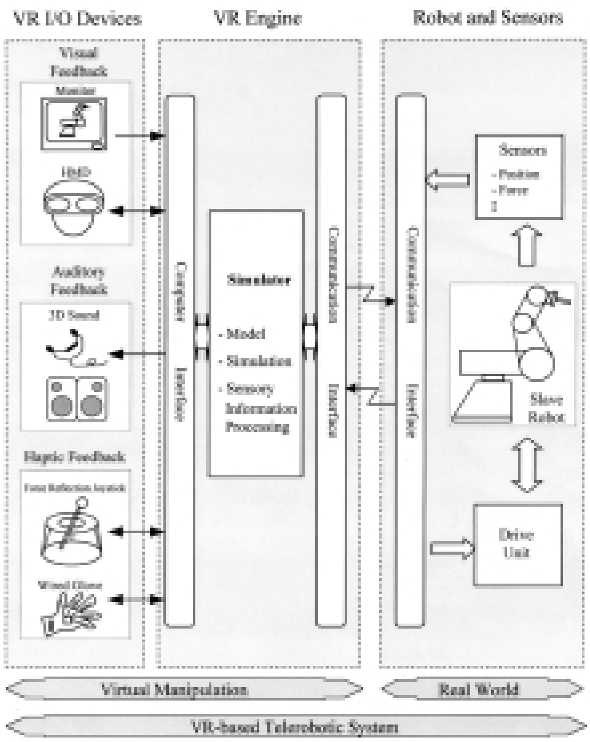

Fig. 1. A VR-based telerobotic system.

Based on the organization shown in Fig. 1, we developed the proposed VR-based telerobotic system shown in Fig. 2. Figure 3(a) shows the system view of this telerobotic system, Fig. 3(b) an example of the virtual robot manipulator in the virtual environment, and Table 1 the major components of the system. As shown in Fig. 2, the human operator sends commands to move the VR robot manipulator in the virtual environment via the input devices: the keyboard, the mouse, and the force-reflection joystick (the Impulse Engine). Simultaneously, motion

(a)

(b)

Fig. 3. (a) System view of the proposed VR-based telerobotic system. (b) The virtual robot manipulator in the virtual environment.

commands are also sent to the RV-M2 drive unit of the Mitsubishi RV-M2 type robot manipulator (Mitsubishi Electric Corporation, Nagoya, Japan), as shown in Table 2, which in turn generates torques to move the real robot manipulator. Actual robot positions are fed back to the VR simulator in the PC1 via the drive unit to synchronize

Table 1. Major Components of the Proposed VR-based Telerobotic System

Platform PC 1	Intel-PC
	Pentium 200
	32 MB RAM
Platform PC2	Intel-PC
	Pentium 120
	32MB RAM
Operation System	Windows 95
Simulation Manager	WorldToolKit for Windows Ver. 2.04
3D Modeling Package	TrueSpace2
Input Device	Keyboard
	PS/2 Mouse
	Impulse Engine
Manipulator	Mitsubishi RV-M2 Type Robot Manipulator
Force Sensor	JR^3 Force-Moment Sensor

the motions of the VR with those of the real robot manipulators. Contact forces induced when the robot manipulator interacts with remote objects are measured using the JR^3 force sensor mounted on the robot manipulator. The measured raw force data are first processed by the JR^3 support system and then sent to the PC2 for further processing. The force data after processing are sent to the force-reflection joystick (the Impulse Engine), as shown in Table 3, to generate a contact feeling and also to the VR simulator to generate realistic VR object deformation. The VR objects are equipped with physical properties corresponding to the real objects; such properties include proper stiffnesses, dampings, etc. (Hirota and Hirose, 1995; McNeely, 1993).

We adopted the concept of distributed processing to implement the proposed telerobotic system. This is because human fingers can discriminate between two consecutive force signals up to about 300 Hz (Shimoga, 1993) while a 30 Hz frame refreshing rate is fast enough for the human eye (Piantanida *et al*., 1993). Therefore, if we process both the visual and force feedbacks in the same simu-

Table 2. Standard Specifications of the Mitsubishi RV-M2 Type Robot Manipulator

Item		Specification	Remarks
Mechanical Structure		5 degrees of freedom robot, vertical articulated robot	
Operation Range	Waist rotation	300º (max. 140º/sec)	J1 axis
	Shoulder rotation	130º (max. 79º/sec)	J2 axis
	Elbow rotation	120º (max. 140º/sec)	J3 axis
	Wrist pitch	±110º (max. 163º/sec)	J4 axis
	Wrist roll	±180º (max. 223º/sec)	J5 axis
Arm length	Offset	120 mm	
	Upper arm	250 mm	
	Fore arm	200 mm	
Weight capacity		Max. 2 kgf (including the hand weight)	
Maximum path velocity		1500 mm/sec	
Position repeatability		±0.1 mm	
Drive system		Electrical servo drive using DC servo motors	
Robot weight		Approx. 28 kgf	
Motor capacity		J1, J2 axes: 60 W; J3: 40 W; J4, J5 axes: 23 W	

Table 3. Standard Specifications of the Force Reflection Joystick (Impulse Engine)

Item		Specification
Degrees of Freedom	Motion and Tracking	5
	Force Feedback	3
Workspace Size		$10 \times 23 \times 23$ cm
Position Resolution		0.0009 in. (1100 dpi)
Max. Force Output		2 lbs. (8.9 N)
Backdrive Friction		≤ 0.5 oz (0.14 N)
Bandwidth	Linear Axis	650 Hz
	Rotary Axis	120 Hz

lation loop, we will not be able to provide a high bandwidth needed for realistic force feedback due to the heavy graphic computation load. A low bandwidth in force feedback may cause instability when the robot manipulator comes into contact with stiff environments, thus leading to an unrealistic contact force feeling. That was why we used two computers to process the visual and force feedbacks separately. Under this arrangement, the updating rate of the force feedback was raised to about 600 Hz. As shown in Fig. 2, the visual signal was processed by computer PC1 and the force data by computer PC2. Two main modules to be developed in these two PCs are: the VR simulator in the PC1 and the force data processor in the PC2, which are discussed below.

1. VR Simulator

The VR simulator in the PC1 was developed to generate virtual environments which imitate real working environments for various compliance tasks. In addition to providing realistic telepresence, the VR simulator can be used for task simulation before real task execution, and it allows one to clear the simulation of secondary factors often present in real working environments, such as inaccuracy, dynamics and inflexibility of the means of control, etc. (Lumelsky, 1991). Furthermore, versatile environments can be generated in short periods of time for various task tests. The two major components in this VR simulator are the simulation manager and the 3D modeling software. The simulation manager accepts the operator's demands and plans when and how those geometrical models in the virtual environment are to be manipulated. The 3D modeling software creates the graphical models of the robot manipulators and the objects in the 3D virtual environment. To reduce the processing time needed for graphical representation and manipulation, the graphical models are constructed using some simple geometrical primitives, such as cones, cuboids, and cylinders, and by using boolean operations to build object, such as intersections, unions, and differences. These graphical models are incorporated with physical properties corresponding to real objects. We used WorldToolKit (WTK), developed by the Sense8 Corporation (Mill Valley, CA, U.S.A.), to develop the simulation manager and TrueSpace2, developed by the Caligari Corporation (Mountain View, CA, U.S.A.), for 3D modeling.

2. Force Data Processor

The force data processor in the PC2 was developed to manage force data. The force data are sent from the JR^3 force sensor system; after processing, the force data are used to generate a contact feeling in the operator's hand via the force-reflection joystick, and also to generate VR object deformation through the VR simulator. The force-reflection joystick is used to receive position commands from the operator and to send reflection forces to the operator's hand. This joystick, the Impulse Engine developed by the Immersion Corporation (San Jose, CA, U.S.A.), has five degrees of freedom in motion, three of which are equipped with force reflection. Its maximal output force is about 8.9 N, providing sensible resistant forces to the operator.

We mounted the JR^3 force-moment sensor (UFS-3012A-25) manufactured by JR^3 Inc. (Woodland, CA, U.S.A.) on the Mitsubishi RV-M2 type robot manipulator to measure the contact forces induced when the robot manipulator interacted with remote objects. The force-moment sensor system consists of a JR^3 monolithic six degree-of-freedom (DOF) force-moment sensor and a JR^3 support system, including a signal conditioning board, a data acquisition board, and a processor board. The JR^3 force-moment sensor provides 6 DOF data: three forces, F_x, F_y, and F_z, and three moments, M_x, M_y, and M_z, in the X, Y, and Z axes, respectively. Before applying this force-sensing system for contact force measurement, it is necessary to perform sensor identification and also to find the mapping between the actual measured force data and the sensor readings. We performed a series of tests to find out how the sensor behaved in various contact directions under various exerted forces. Four standard counterpoises with weights of 100, 200, 500, and 1000 g were used to exert forces on the Z axis of the sensor and on the eight directions uniformly distributed on the X–Y plane spanned by the X and Y axes. Results show that the sensor presented consistent readings in all those directions in tests conducted under the same exerted forces and linearly proportional readings along with increasing exerted forces in the same direction, indicating that this force sensor was quite accurate and ready for force measurement in the following experiments.

III. Force Reflection

Due to the transmission time delay and the incompatibility between the manipulative devices used by the operator and the slave robot manipulator at the remote site, the operator usually experiences unnatural and ineffective manipulation when teleoperating the slave robot manipulator to perform compliance tasks. To furnish the operator with better flexibility in force management, we propose using force-reflection strategies installed in the virtual side to generate virtual reflected forces, as opposed to receiving contact forces measured directly by the force sensor mounted on the slave manipulator (Anderson and Spong, 1989; Chan *et al*., 1997; Kim *et al*., 1992; Repperger *et al*., 1995). With this design, because the reflected force is acquired locally, time delay is alleviated; thus, the operator can feel stable reflected forces. One key ingredient for success with the proposed approach is accurate mapping between the virtual and real environments, so that the generated VR reflected force will approximate the real reflected force. Two VR force-reflection strategies were used: virtual force field and VR force reflection. In addition, we implemented the direct force reflection strategy for comparison, in which the interactive forces between the slave robot and the remote objects are fed back to the operator directly. In addition, to get realistic descriptions of the object behaviors in response to the forces induced during interaction between the robot manipulator and remote objects, we implemented VR object deformation.

1. Virtual Force Field

The concept behind the virtual force field method is to generate a force field around the obstacle, so that the operator will feel a resistant force when the slave robot is very close to the obstacle. We use a spring model to describe the interaction which occurs when the slave robot is pushed into the force field:

$$F = K \times X, \tag{1}$$

where F stands for the virtual force reflected to the operator, K the virtual stiffness of the force field, and X the distance by which the slave robot is pushed into the force field.

2. VR Force Reflection

The basic idea behind the method of VR force reflection is to generate the VR reflected force using the estimated stiffness of the remote object derived from the measured position and force data, as described in Eq. (2):

$$F_c = K_o \times (X_a - X_c), \tag{2}$$

where F_c stands for the generated reflected force, K_o the estimated object stiffness, X_c the location of the contact surface, and X_a the robot position. In addition allowing consideration of time delay, use of the estimated stiffness for VR force generation can also avoid the sensitivity problem usually encountered when the sensed force is used directly. The least-square linear regression method was used to estimate the real-time stiffness by processing a series of continuously measured position and force data. With the real-time stiffness estimation, the method can deal with varying stiffnesses and, consequently, with unknown environments.

3. VR Object Deformation

We use the spring model to generate VR object deformation due to the forces induced when the slave robot interacts with remote objects. Thus, the operator can also visualize the effect of the interactive force as well as feel the reflected force. To speed up the graphical display, we did not implement entire shape varying during object deformation but approximated the curved surfaces of the deforming object by linearly varying planes.

Note that for the two proposed VR force-reflection strategies and object deformation generation, we adopted a simple spring model for force generation. To be more general, a masss-pring-damper model can be used, as described below:

$$F_c = M_o \times \ddot{X}_a + B_o \times \dot{X}_a + K_o \times (X_a - X_c), \tag{3}$$

where M_o, B_o, and K_o stand for the mass, damping, and stiffness, respectively.

IV. Experiments

We designed a series of experiments to evaluate the effects of virtual reality and force-reflection strategies on operation of the proposed telerobotic system used to perform compliance tasks. In the first set of experiments, the users were asked to move the end-effector of the slave robot to pass through a maze from the start position to the target region, as shown in Fig. 4(a), using the force-reflection joystick. We intended to use the experiments to answer the following questions:

(1) Does VR help the operator in task execution?
(2) Does force reflection help the operator in manipulation?
(3) Is direct force feedback or virtual force feedback more helpful?

Eight subjects, men and women in their early twenties, were asked to perform the experiments. Two of them were quite familiar with the proposed telerobotic system while the other six were not. Each of them executed the maze-passing experiment using the following five manipu-

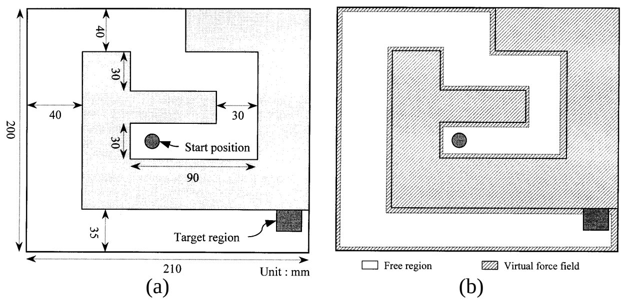

Fig. 4. (a) The maze setup. (b) The walls in the maze equipped with virtual force fields.

lation methods:

(1) Method 1: manipulation by looking at the real environment directly.
(2) Method 2: manipulation in the virtual environment without force reflection.
(3) Method 3: manipulation in the virtual environment using direct force reflection.
(4) Method 4: manipulation in the virtual environment using VR force reflection.
(5) Method 5: manipulation in the virtual environment in the presence of VR force fields (Fig. 4(b) shows the walls in the maze equipped with virtual force fields).

Performance was evaluated based on the elapsed time and the contact force during task execution. We recorded both the total and average contact forces because the task execution time might be different in various cases. Figure 5 shows the results for this maze-passing experiment. In Fig. 5, the maximum and minimum values yielded by the subjects for each method are indicated by cross bars at the top and bottom, respectively, and the average value is indicated by a little circle. The experimental results are summarized and discussed in the following:

(1) Method 1 yielded better performance than Method 2 did. We think this was because the VR simulator gave the operator better views and various viewing angles to look at the remote environment. We concluded that VR did help the operator in teleoperation.
(2) Judging from the task execution time, we found that Methods 3, 4, and 5 yielded better performance than Methods 1 and 2 did. We concluded that additional information provided by force reflection did help the operator in manipulation.
(3) Methods 4 and 5 yielded better performance than Method 3 did for both task execution time and contact force. In Method 3, using direct force reflection led to bouncing between the walls in the maze due to the transmission time delay and the high stiffness of and narrow passages between the walls, and thus resulting in large contact forces and even instability. In contrast, virtual force feedback generated using Methods 4 and 5 did not induce instability because there was no transmission time delay or noise, thus leading to higher bandwidth in force generation. We concluded that virtual force feedback was more helpful than direct force feedback was.
(4) Method 3 yielded larger contact forces than Method 2 did in some cases. This indicated that the inclusion of an arbitrary force-reflection strategy did not necessarily reduce the contact force. On the other hand, skillful operators could use visual feedback alone to achieve good performance, indicating that visual feedback was a more important factor than force feedback was.
(5) Method 5 yielded better performance than Method 4 did. This was because the goal in this maze-passing experiment was to pass through the maze quickly while minimizing the contact force. By

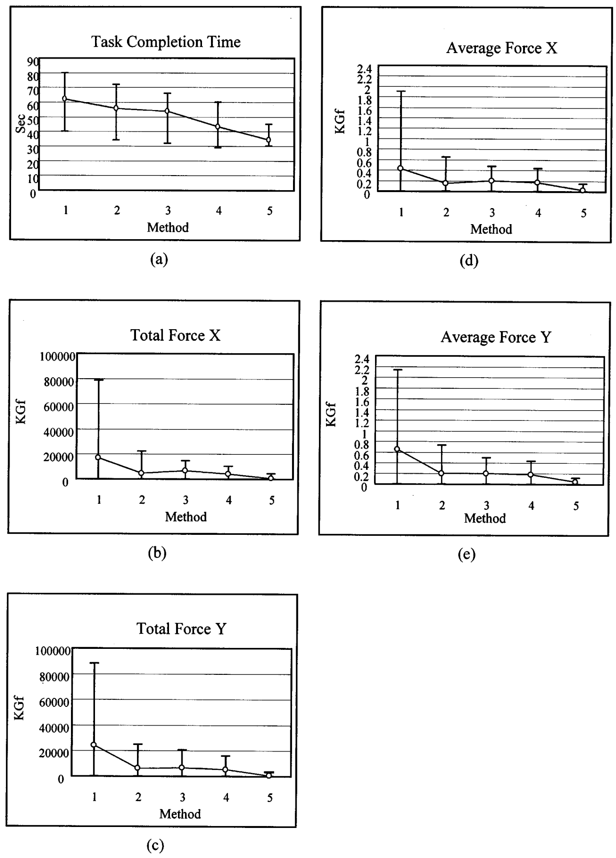

Fig. 5. Results for the maze-passing experiments: (a) task execution time, (b) total contact force along the X direction, (c) total contact force along the Y direction, (d) average contact force along the X direction, and (e) average contact force along the Y direction.

sliding along the boundary of the virtual force field, Method 5 avoided contact with the walls of the maze. We concluded that the virtual reality technique combined with a VR force-reflection strategy most suitable for the characteristics of a given compliance task could achieve the best performance.

For compliance tasks demanding contact with the environment, the virtual force reflection used in Method 4 may be more suitable than the virtual force field in Method 5. In the second set of experiments, we used Method 4 to manipulate the slave robot so as to track the boundaries of two hard objects: an aluminum cuboid (128 mm × 55 mm × 55 mm) and an aluminum cylinder with a radius of 45 mm; experiments were also executed using Method 3 for comparison. Figure 6 shows the results of contour following using Methods 3 and 4 for (1) the aluminum cuboid (Fig. 6(a)) and (2) the aluminum cylinder (Fig. 6(b)), in which the boundaries of the objects are indicated by dotted lines, the contours generated by applying VR force reflection by solid lines, and those generated by applying direct force reflection by dashed lines. As shown in Fig. 6, large oscillating contact forces were observed when direct force reflection was used while VR force reflection yielded salient contour following with stable contact forces, indicating that the proposed VR force reflection estimated the stiffnesses of the hard objects quite well in real time.

V. Conclusion

In telerobotics, the human operator is an important part of the control and decision-making loop, especially when complex applications are involved (Lumelsky, 1991). In this paper, we have proposed several force-reflection strategies, described the implementation of a VR-based telerobotic system, and evaluated how these techniques influenced the human operator in performing compliance tasks that demand refinement and force management. Via a series of experiments, we have shown that properly using virtual reality and force reflection in a telerobotic system makes it possible to generate realistic telepresence and to provide a contact sensation during compliance tasks. In future work, this VR-based telerobotic system will be improved in several ways. To obtain more realistic object models, we plan to build into the models more physical properties, such as mass, damping, and others. To generate more realistic object deformation, we will consider force distribution in the entire object and apply the deformation process to each location on the object, instead of approximating object deformation by varying planes. Also, in addition to providing force reflection to the operator for decision making, we will develop force control strategies for the telerobotic system so as to alleviate the control load on the operator by allowing the slave robot to do some control jobs autonomously.

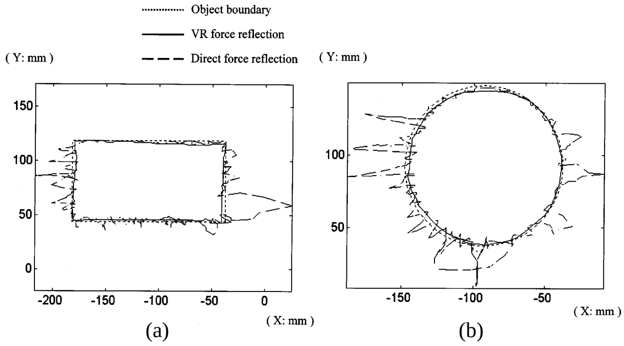

Fig. 6. Contour following achieved by using direct force reflection and VR force reflection for (a) an aluminum cuboid and (b) an aluminum cylinder.

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於虛擬實境中發展之具力反映能力的遙控機器人系統

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摘　要

本文中我們報告一在我們實驗室所發展的遙控機器人系統。遙控機器人極適合應用於危險或未知的環境，而如何使操作者能對遠端環境有臨場感，能感受到機器人與外界物件互動產生的接觸力，是遙控機器人系統極大的挑戰。我們利用虛擬實境技術來發展遙控機器人系統，我們也賦予此系統力反映能力，使其能應用於需精巧操作與順應性控制的工作。