研　究　速　報

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Virtual Reality-Based Teleoperation in the Micro/Nano World

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1. Introduction

One of the main challenging matters for micro/nano scale object manipulation is the micro/nano physical and chemical phenomenon which is still not completely understood. Therefore, it is very early for automatic manipulation systems, and teleoperation technology at the initial phase is a promising tool for understanding these uncertainties and improving automatic manipulation strategies using the human intelligence. Therefore, a teleoperation system with Virtual Reality (VR) user interface is proposed for micro/nano manipulation applications in this study.

In the literature, two groups use teleoperation for micro/nano manipulation depending upon our knowledge. Hollis et al. [1] utilized STM probe as the slave-robot and 6DOF fine motion device called Magic Wrist as the master device for feeling atomic scale topography in operator's hand. They tried to feel the topology of gold and graphite, but there were problems of mechanical and electrical noise which deforms the tactile feeling, and no true force-reflecting behaviour. Another group [2] utilizes commercial Atomic Force Microscope (AFM) and haptic device for real-time haptic display, but they do not have any report on teleoperation control problem.

2. Virtual-Reality Visual Display

Real-time and interactive visual feedback from the nano world which gives information about surface roughness, shape, texture, etc. is essential besides of haptic feedback. For this purpose, using Virtual Reality graphics technology, two systems are constructed: *Nano Visulator* (NV) [3, 4] as shown in Figure 1 and *Nano Animator/Simulator* (NA/S). The former is for presenting the 3-D topology image as a shaded image to the user such that the image can be rotated, zoomed, etc. in an interactive way. The latter combines visualization with nano-physics where the nano forces and dynamics can be simulated in a graphics environment. Thus, connecting with force display, training and feasibility tests can be realized before the experiments, and, during manipulation since there is no real-time visual feedback, this deficiency can be eliminated by animating the object motions during manipulation using NA/S tool.

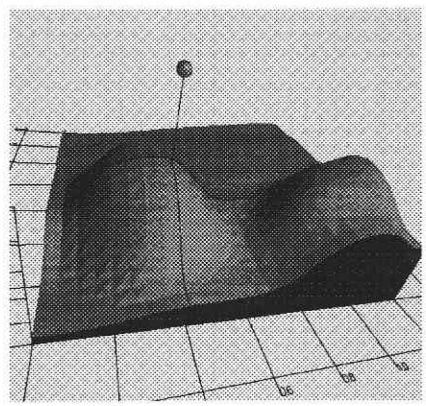

Fig. 1 VR Visulator for micro/nano teleoperation (ball represents the micro/nano manipulator gripper).

3. Force Display

For feeling the interatomic force normal to the AFM tip (lateral forces are excluded in this study), a 1DOF master device is constructed [5]. Operator puts his/her hand to the master arm, applies the normal force $F_m(t)$, moves it with $x_m(t)$, and meanwhile feels the scaled nano forces by applied motor torque. The arm is *admittance type* such that there is almost no power transmission from operator to the master arm.

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4. Bilateral Teleoperation Control

During approaching and contacting to the surfaces or objects at the micro/nano world, the operator controls the x-y-z motion of the cantilever/sample while feeling the normal tip-sample interaction force. Using linear scaling approach, at the steady-state, the ideal response of the bilateral teleoperation system is defined as:

$$F_m \rightarrow \alpha_f F_s$$
$$x_s \rightarrow \alpha_p x_m$$

where $F_m(t)$, $F_s(t)$ are operator and nano forces, and $x_m(t)$ and $x_s(t)$ are positions respectively.

In order to realize the ideal responses, the bilateral teleoperation system in Figure 2 is proposed. Virtual Impedance (VI) control approach is utilized to control the impedance between the master and slave arms for realizing the desired force feedback depending on the task. Thus, VI control transfer function term $V(s)=1/(M_V s^2 + B_V s + K_V)$ generates smooth reference master and slave positions as $x_{mr}=x_{sr}/\alpha_p$ since it also behaves as a second order low-pass filter. $M(s)$ and $S(s)$ are master and slave overall (plant and control) transfer functions. K_f is the force error feedback gain. At the steady state, $x_s=\alpha_p x_m$, and, in the case of a constant spring dynamics for the tip-nano object interaction, i.e. $F_s(s)=KX_s(s)$, the following equality is held for the forces:

$$\frac{F_m}{F_s} = \frac{K_v}{\alpha_p K K_f} + \alpha_f \quad \cdots\cdots (1)$$

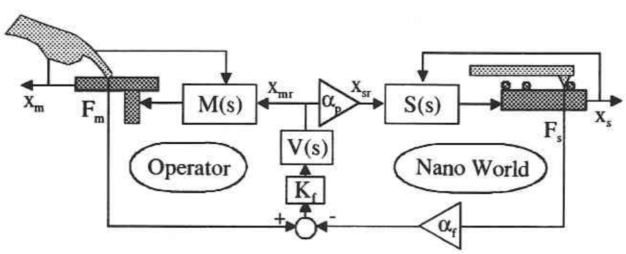

Fig. 2　Scaled bilateral teleoperated force feedback control system setup.

For the ideal responses, $K_V=0$, or $K_f>>K_V$ condition should be provided. Furthermore, assuming the operator and nano object-tip interaction dynamics are passive, and providing the ideal responses, the system stability is also held.

5. Experiments

Two main experiments have been realized for testing the feasibility of the teleoperation control by touching to a point on a surface, tactile feedback by touching to many points on nano surfaces, and manipulation control by latex particle 2-D assembly experiments. At first, bilateral teleoperation scheme is tested. Touching to a point on a silicon surface results in the operator and nano force and position as shown in Figure 3. Parameters of the system are $M_v=0.1kg$, $B_v=2N/(m/sec)$, $\alpha_p=8x10^4$, $\alpha_f=25$, $K_f=30$, $K_{mP}=5$, $K_{mI}=0.5$, and $K_{mD}=0.05$. Initial tip-sample position is approximately $100nm$, and z motion steps are around 10-20nm. As can be seen in the force-time graph, the operator starts to apply force at around 0.6*sec*. Then the master device also begins to move until to the contact point. After the contact, ideal response is being held where scaled forces and positions follow similar shapes. The position offset is due to the piezoelectric actuator offset, and the force offset is due to thermal drift at the deflection measurement hardware and noise which limits α_f.

Next, a silicon fabricated square-shape periodic structure as shown in Figure 4a is felt by the operator by moving in x-y using

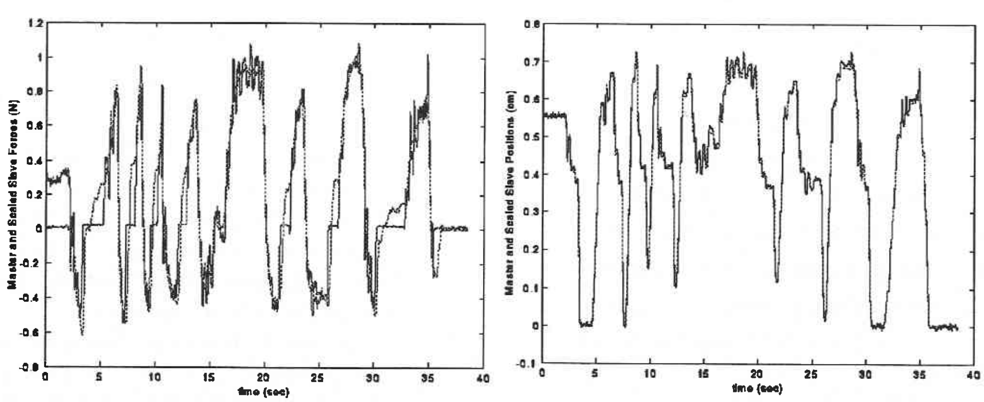

Fig. 3　Touching vertically to a point on a silicon substrate: the master (solid) and scaled slave (dashed) forces (left), the master (solid) and scaled slave (dotted) positions (right) vs. time.

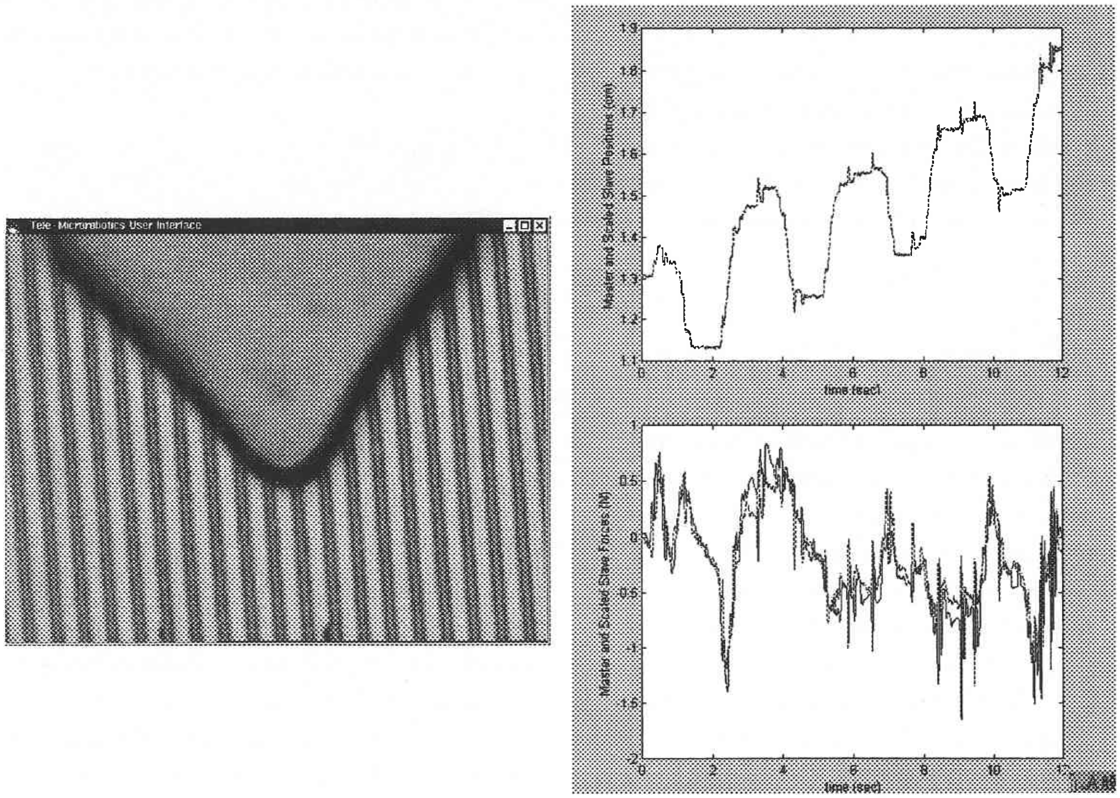

Fig. 4 (a) Optical Microscope top-view image of silicon fabricated square periodic structure and AFM cantilever, (b) The surface feedback on the operator hand: master and scaled slave positions (upper) and forces (lower) data.

the mouse cursor. Square shape of the surface is felt successfully while the teleoperation controller enables also force-feedback tracking as can be seen in Figure 4b.

6. Conclusion

In this paper, a VR user interface system micro/nano manipulation applications is proposed. Besides of 3-D visual feedback in the user interface, a 1-DOF haptic device has been constructed for micro/nano scale force sensing and generating motion commands for the micro/nano manipulator. Introducing teleoperation control system with Virtual Impedance approach, nano scale forces or topologies are felt by the operator. Preliminary experiments on tactile feedback from surfaces at the micro/nano scale show that the system can be utilized for teleoperated micro/nano manipulation applications.

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