Virtual Reality User Interface for Teleoperated Nanometer Scale Object Manipulation

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Abstract

In this paper, a user interface for the teleoperated nanometer scale object manipulation is introduced. A 3-D Virtual Reality computer graphics display presents the topology of the nano world to the user, and a 1DOF haptic device used together with a 2-D conventional mouse is the master manipulator, and also enables force and tactile feedback from the nano world. Preliminary experiments on the user interface shows that the interface can be utilized for the Tele-Nanorobotics applications such as 2-D assembly of nano particles and biological object manipulation.

1 Introduction

In recent years, tele-operation technology has been developed such that operators can control robots at the remote sites such as in an outer space, a hazardous environment, an nuclear plant, and so on. Using this tele-operation technology micro/nano scale objects can also be considered as the remote target objects to be manipulated. Since the human being cannot directly see, touch, move, and manipulate objects in the nano world, a teleoperation system can be a possible solution for the human-nano world interaction.

The invention of the Scanning Tunneling Microscope and the Atomic Force Microscope (AFM) enables the 3-D imaging down to atomic scale in the nano world. These devices utilize a probe with nanometer size sharp tip to interact with the surface atoms locally, and get a constant effect related to the surface topology, or other physical properties. Although the imaging is possible in the nano world, manipulation of the nano objects has not been established yet. For this purpose, probes of these microscopes can also be considered as a simple nano manipulator, and utilized in manipulation tasks as push or pull, pick and place, cutting, etc.

For the teleoperated nano manipulation, the user-friendly man/machine interface part of the system is very important. Hollis et al. [2] constructed the teleoperated atomic scale tactile-feedback system utilizing STM as the slave device and the 6 DOF device called Magic Wrist as the master device. Furthermore, R. M.Taylor II et al. [3] constructed the force-feedback Nanomanipulator system utilizing STM as the slave and the Force-Feedback Argonne-III Remote Manipulator as the master device, and a Head-Mounted Display was adopted to provide an immersive virtual environment created by the Pixel-Planes 5 graphics engine.

In this paper, a user interface for the Tele-Nanorobotics System proposed in [9] has been presented. The goal of this system is to manipulate and assemble the nano scale objects easily in order to fabricate the nano parts of micro machines and manipulate the biological objects such as a gene or DNA.

2 System structure

2.1 Setup

In the Tele-Nanorobotics System, AFM is chosen as the visual and force sensing device, and also the nano manipulator. An AFM can measure force as well as 3-D topology and can be used for any material. The main components of this system are the AFM cantilever, the cantilever deflection detection hardware, the nanometer and higher resolution positioning system, and samples. Main controller of the system is the PC which has Pentium 166 MHz CPU, 32 MB RAM, Windows 95 OS, 16 bit A/D board, and 12 bit D/A board. The overall system is shown in Fig. 1.

In this system, the AFM measures the force between the cantilever tip and a sample, and the topology of the sample. These data are transmitted to the PC using A/D board. On the other hand, AFM position control commands are transmitted from the PC to the position

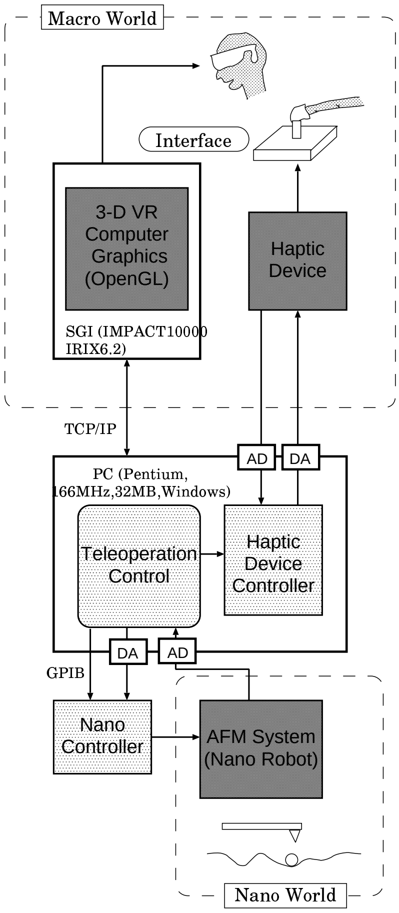

Figure 1: Tele-Nanorobotics System.

controller by using a GPIB connection. Furthermore, the topology data is transmitted to SiliconGraphics Workstation (IMPACT 10000, IRIX 6.2) from PC by using TCP/IP (Ethernet 10Mbps).

2.2 AFM : Slave Device

AFM can measure the interatomic force between atoms of sample surface and the cantilever tip, which is attractive or repulsive depending on the distance between the sample and the tip. When the tip-sample distance is more than $0.3nm$ the force between the sample and the tip is attractive, but on the other hand, when less than $0.3nm$ it is repulsive. When a reference value of force is selected, the cantilever moves to the position until the force becomes the same value. Thus the height of samples is measured and scanning all surface gives the 3-D topology of samples surface [9].

The AFM tip behaves not only as a mesurement tool but also as the 3-DOF nano robot to simply push and pull the nano objects. 2-D assembly of nano particles or biological objects can be realized by this nano robot. The contact mode is used for the AFM operation mode, and the handmade AFM system is constructed.

In this system, the position $x_s(t)$ of not the AFM tip but the sample is moved by controlling the voltage $V_t(t)$ of the piezotube. The teleoperation control aims to get the response of $X_s(s) \rightarrow S_x X_m(s)$ and $F_{op} \rightarrow S_f F_n$ when $t \rightarrow \infty$, where S_x is the position scaling factor, S_f is the force scaling factor, $X_m(s)$ is the master position, F_{op} is the operator force, and F_n is the nano force.

3 User Interface

3.1 Ideal user interface

Generaly some charactristics are requested for the user interface, such as the easiness to control, to be understood intuitively, less fatigue, etc. For the nano teleoperation user interface, the following features are required:

- the easiness of seeing and recognizing the nano world where we can not see the nano world directly,
- the ability to control finely not to break the AFM tip and samples, because samples become very soft in the nano world and the distance between the tip and sample is very small,
- the realness of the feeling of the nanoscale forces and topologies in the macro world.

3.2 Visualization

3.2.1 Aim

During controlling, building, or manipulating nano objects, the visual feedback, to see what the operator does, is very important since we have many uncertainties in the nano world.

An optical microscope is inadequate for visualizing in the nano world. The Rayleigh criterion limits the resolution d to a few hundred nanometers, based on the equation:

$$d = \frac{1.22\lambda}{NAcond + NAobj}, \quad (1)$$

where λ is the wavelength, and $NAcond$ and $NAobj$ is the numerical aparture of condenser and objective, respectively [7]. In our system, d is $671nm$ where $NAcond = NAobj = 0.5, \lambda = 550nm$.

Scanning Electronic Microscope has also long proved success in visualizing down to tens of nanometer resolution. However, it can provide only 2-D images, the working area is restricted to the vacuum, and biological samples such as cells can not be visualizad since their electrical properties can change.

We adopted the OpenGL 3D graphics software library to show the nano world. The height data of a sample is transmitted from PC to SGI by using TCP/IP network with 10Mbps. On the SGI, the 2D black and white image using X11 library is also running, which can show the position of the AFM cantilever. The 3D image can be rotated, zoomed, and changed its height scale by the software. The 2D image and the 3D image are connected to each other. An example of the visual interface on the SGI display is shown in Fig. 2.

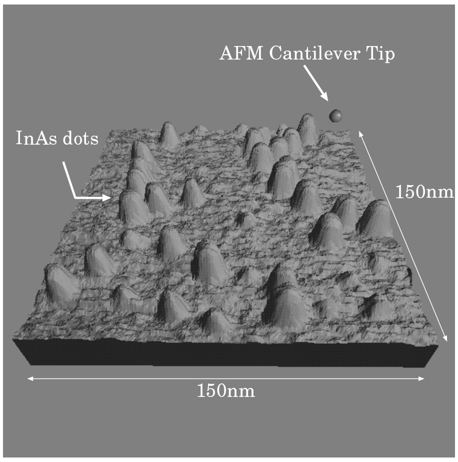

Figure 2: 3-D virtual reality graphics image of InAs dots with around $5nm$ radius and $10nm$ height on the InAs surface with the size of $150 \times 150nm^2$ interface.

3.2.2 User Modes

Considering the procedure of the nano manipulation in this system, there are three steps as shown in Table 1.

The first step is an *image viewer*: scanning a sample surface, sending the data to graphic software, and displaying the topology. At this step, the nano scale height data at the x-y position (i, j) is transformed to the graphic data as follows:

$$r_{ij} = (i\Delta x, j\Delta y, z_{ij}), \quad (2)$$

Step	
1	Image viewer
2	Setting environments
3	Operation

Table 1: Procedure steps.

where $i = 0, \ldots, (S_x - 1)$, $j = 0, \ldots, (S_y - 1)$, Δx is the step length when scanning the surface in x direction, Δy is the step in y direction. Usually these steps are the same, $\Delta x = \Delta y = \Delta$. S_x and S_y are the maximum number of points in the scanning range in x and y directions, respectively. The point (i, j) is transformed to the position in the 3D image as:

$$(i, j) \to (i - (int)(S_x/2), j - (int)(S_y/2)) = (i', j') \quad (3)$$

After this translation, the point $(i'\Delta x, j'\Delta y, z_{ij})$ is drawn in the 3-D image.

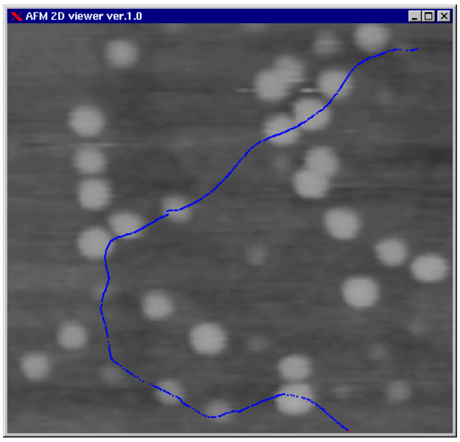

Figure 3: 2-D grey scale display of an AFM data. The line is the trace of the mouse.

The 3-D image can be presented to the user in different ways such as using a 3-D glass, a Head Mounted Display, or shaded image on the computer display. At present, only the shaded image is being used. Moreover, a 2-D grey-level image is also displayed in order to facilitate the x-y motion intuition from upper viewing. 2-D grey-level image color depends on the height such that the higher is the point, the brighter is the color as shown in Fig. 3.

The second step is *setting control environment*: rotating and zooming the sample to select the best angle and size to see, and changing the color of the surface.

This mode is for selecting the user-selected best parameter to visualize, such as selecting the view point, colors, angle, zoom, etc.

The last step is the operation step where there are three kinds of operations for the time being as shown in Table 2: force-feedback, tactile-feedback, and manipulation modes.

1. *Force-feedback mode* is for feeling the local force interaction between the tip and the sample. In this mode, no object moves, no position feedback, therefore no image update. User moves the tip in the z direction at the one point or on a line, the tip is moved by the force and the user feels the atomic force.
2. *Tactile-feedback mode* is for feeling the position of the sample, i.e. geometry feedback. In this mode, also no objects move, no image update, but only the position feedback is done where the force is automatically set to be a constant value.
3. *Manipulation mode* is for manipulating the nano objects. In this mode, there is a real-time force feedback, objects are movable, and image is updated.

3.2.3 Requirements for visualization

The requirements for the graphics are different depending on the mode as described above. At first, the cantilever position (x, y, z) should be shown in real-time at every mode, and especially in force and tactile feedback. Secondly the sample image should be updated in the manipulation mode after each manipulation tasks. Thirdly the deformation and the position-change of the objects can also be shown during the manipulation mode. At the present, the first two requirements are realized, and the third is a future work.

3.3 Master device

3.3.1 Functions/Modes

The haptic modes of the master device are the same as the operation modes in the visualization, which are the force-feedback, the tactile-feedback, and the manipulation mode. The haptic device and AFM cantilever interaction in each mode is shown in Fig. 4-6.

In the *force-feedback mode* as shown in Fig. 4, the teleoperation controller is designed for getting the following ideal responses:

$$F_{op} = \alpha_f F_s, \tag{4}$$

$$X_s = \alpha_p X_m, \tag{5}$$

where F_s and X_s are the tip force and position respectively, F_{op} is the operator force, X_m is the haptic device position, and α_f and α_p are the scaling factor for the force and the position respectively. An operator can feel the normal force at any point (x, y, z) on the sample.

In the *tactile-feedback mode* as shown in Fig. 5, an operator can feel not the force but the topology of samples, using only the Eq. (5). The force control is that F_s keeps the constant value, that is the height is constant.

In the *manipulation mode* as shown in Fig. 6, ideal responses at the equations (4) and (5) are used. In this figure, F_1 is the inercial force between the AFM tip and an object, F_2 is the force between the surface and an object, F_3 and F_4 are the friction. The modeling of these forces is the difficult issue for the manipulation where they are mainly attractive, repulsive or friction forces, and the gravity is ignored [4].

3.3.2 Requirements for the Haptic Device

In the case of the haptic device to manipulate the nano objects, the special characteristics different from an ordinary device are requested. The first is the high speed response because the phenomenon in the nano world is faster than the macro world. Another is the ability to feel the 3-DOF (x-y-z) attractive or repulsive nano forces with dimensions around $nN - pN$. The first one influences the mechanism of the device, and the second influences the teleoperation control parameters such as a scaling factor.

On the other hand, for the convinience to an operator, an enough work space, a good design to use, and many degrees of freedom (at least 3DOF and at most 6DOF) are neccesary. Furthermore, for force-feedback at least over $50Hz$ bandwidth is requested.

3.4 Haptic device control

In this system, the 1DOF haptic device as shown in the Fig. 7 is used for the z direction force feedback, and the mouse is used for the x-y direction control without force feedback. The details of this haptic device control is given in [8].

An operator puts his/her finger on the master device, applies the force $F_{op}(t)$ to the device, and feels the motin $x_m(t)$ of the arm.

The teleoperation control utilizes the virtual impedance model. The tactile-feedback mode does not use the bilateral tele-operation control but only uses the control as shown in Eq. (5). The details of this teleoperation control are given in [9].

	Objects	Image Update	Position feedback	Aim
force-feedback mode	NOT Movable	No	Off	Feeling force
tactile-feedback mode	NOT Movable	No	On (F=const)	Feeling position
manipulation mode	Movable	Yes	Off	Manipulating

Table 2: Operation mode.

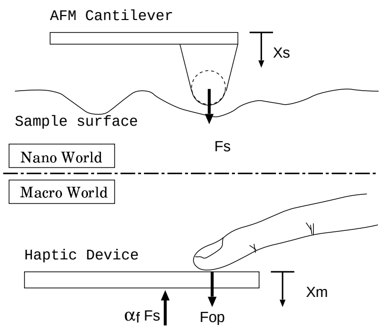

Figure 4: Force feedback mode.

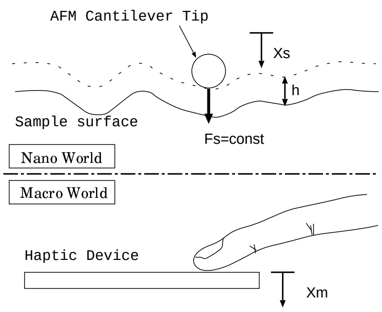

Figure 5: Tactile feedback mode.

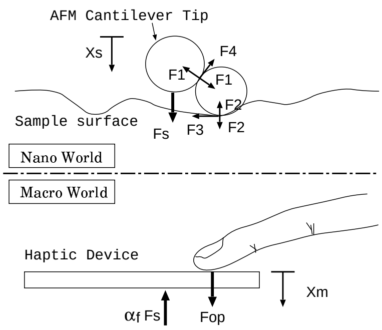

Figure 6: Manipulation mode.

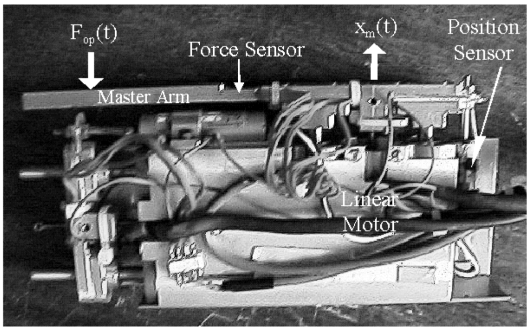

Figure 7: 1DOF haptic interface with a linear moter, and force and position sensors.

4 Experiments

In the tactile-feedback mode, the measured3-D topology are felt on the operator's finger while scannning a sample. At first, the cantilever tip is approached to the surface, and contact it. By controlling the x-y position on the 2D window with the mouse, the operator who puts his/her finger on the haptic device can feel the relative height of the surface by the position change of the device control. As the experimental result, the trace of the mouse, the height of the traced points, and the position of the haptic device are shown in Fig. 8.

According to this result, the distance between the tip and the sample looks like almost constant. Thus the tele-operation control is well done. The delay time, from when the click the point to move $x - y$ point to when the haptic device is controlled to the relative height, takes about $500msec$. Furthermore, the update rate for a 100×100 pixel size image in the 3-D virtual reality graphics system is approximately $2sec$ while the the scanning time of a sample with 100×100 pixel size is around $10min$ which is due to the AFM hardware scanning and positioning speed, and PC-controller communication delay. The AFM hardware will be enhanced for faster imaging. The other delays are due to the TCP/IP communication time (between the mouse and the AFM system) and the cantilever position control time. Moreover, writing to and reading from the Shared Memory delays the 3D drawing.

5 Conclusion

In this paper, a user interface for the teleoperated nanometer scale object manipulation is introduced. A 3-D Virtual Reality computer graphics display presents the topology of the nano world to the user, and a 1DOF haptic device together with a 2-D conventional mouse enables force and tactile feedback from the nano world. Preliminary experiments on the user interface shows that the interface can be utilized for the nano object manipulation applications. However, some problems still remain such to be solved as the time delay. In order to reach the first goal of the 2-D assembly, the future work includes expanding the haptic device to 6DOF, decreasing the time delay, and constructing a new device for x-y positioning.

References

[1] P. H. Beton, A. W. Dunn, and P. Moriarty, 'Manipulation of C_{60} molecules on a Si surface', Appl. Phys. Lett., Vol. 67, No. 8, pp. 1075-1077, 1995.

[2] R. L. Hollis, S. Salcudean, and D. W. Abraham, 'Toward a tele-nanorobotic manipulation system with atomic scale force feedback and motion resolution', IEEE Int. Conf. on MicroElectromechatronical Systems, pp.115-119, 1990.

[3] Russel M.Taylor II, Warren Robinett, Vernon L. Chi, and et al., 'The Nanomanipulator : A Virtual-Reality Interface for a Scanning Tunneling Microscope', SIGGRAPH Computer Graphics Proc., Annual Conf. Series, pp.127-134, 1993.

[4] M. Sitti and H. Hashimoto, 'Macro to Nano Tele-Manipulation through Nanoelectromechanical Systems', Proc. of the IEEE Ind. Electronics Conf., (to be published), Germany, 1998.

[5] K. Kaneko, H. Tokashiki, K. Tanie, and K. Komoriya, 'A Development of Experimental System for Macro-Micro Teleoperation', IEEE Int. Workshop on Robot and Human Communication, pp. 30-35, 1995.

[6] H. Miyazaki, and T. Sato, 'Pick and Place Shape Forming of Three-Dementional Micro Structures from Fine Particles', Proc. of Int. Conf. on Robotics and Automation, pp. 2535-2540, 1996.

[7] A. Stemmer, H. Jacobs, and H. F. Knapp, 'Approaching the nanoworld', Proc. of the Int. Society for Optical Eng., Vol. 2906, pp. 80-85, 1996.

[8] S. Manorotkul, 'Tele-Handshaking through the Internet', M.Sc. Thesis, Dept. of Electrical Engineering, Institute of Industrial Science, Univ. of Tokyo, 1996.

[9] M. Sitti and H. Hashimoto, 'Tele-Nanorobotics using Atomic Force Microscope', Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robot and System, (to be published), Canada, 1998.

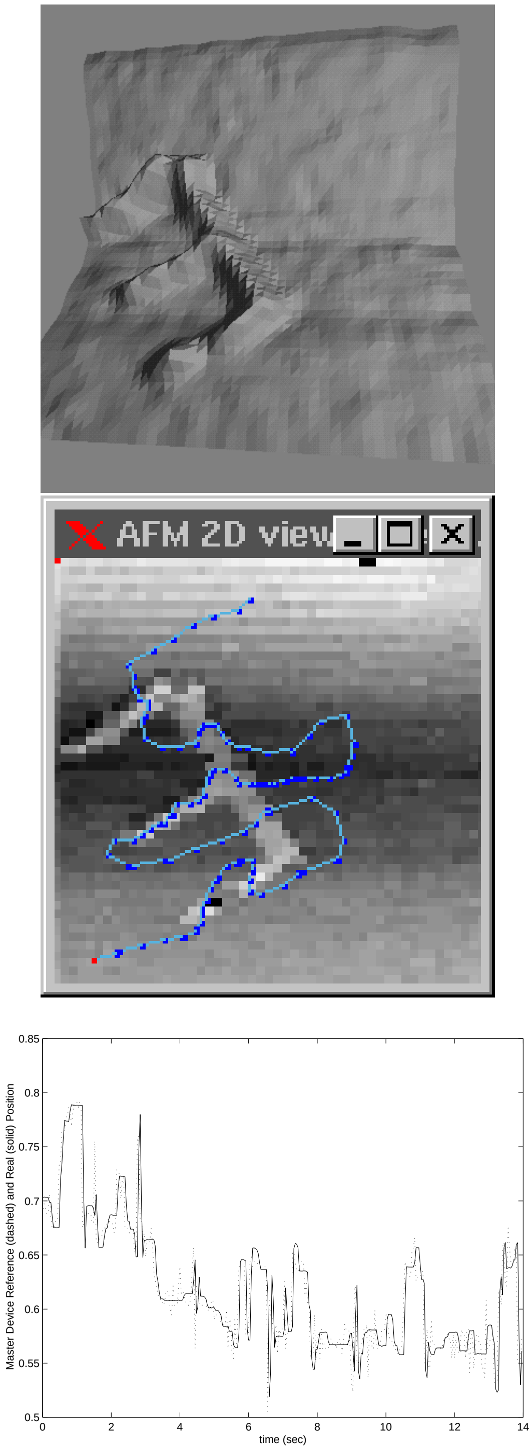

Figure 8: Tactile-feedback mode result : Silicon sample surface with FIB etched number and $10 \times 10\mu m^2$ area is scanned. 3-D graphics (upper), 2-D image with mouse traces (middle), and resulting haptic device tactile feedback (lower) are given.