Visualization Interface for AFM-Based Nano-Manipulation

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Abstract—**In this paper, ideal interface characteristics for nano scale object manipulation using Atomic Force Microscope (AFM) is discussed. Nano manipulation technology using Scanning Probe Microscope such as AFM or Scanning Tunneling Microscope (STM) has been introduced recently. Nano world physics is different from the macro world such that the gravity can be ignored while the influences of sticking forces such as the capillary or the van der Waals forces are dominant. Furthermore, the precise tip position control in the z direction is important for not breaking the tip or the samples. Depending on the experimental results, besides of graphical displays, the visualization of the force value is important to control the z position.**

I. Introduction

By the recent advances on micro/nano-mechatronics technology, the size of devices and machines has become smaller and lighter. Some researhers are trying to construct the ideal miniature devices by manipulating and assembling the atoms or molecules where this approach is called *bottom-up* approach [1], [2], [3]. On the other hand, the *top-down* approach tries to make smaller machines using large machines by improving the precision of the manipulation [4], [5]. This kind of still infant micro/nano manipulation technology has many potential application areas such as biological manipulation, terabit hard-disk memories, new types of materials, and etc.

As an example of molecular manipulation, Eigler et al., IBM Zurich Research Laboratory, manipulated the xenon atoms to write the letter "IBM" using the STM [6], [1]. Although various researchers manipulate the nano scale objects [7], [2], they do not have user-friendly interfaces to manipulate objects with teleoperation utilities, and they mostly utilized trial and error approach. Therefore, necessity to adopt the telerobotics approach and to construct user-friendly interfaces have emerged. At this point, many researcher have proposed teleoperated micro scale object manipulation systems [5], [8], [4]. For the nano scale object manipulation case, two systems have utilized AFM and STM with haptic and visual displays: Hollis et al. [9] used STM for tactile feedback, and Taylor et al. [10] used AFM and commercial haptic devices, and introduced virutal reality gaphics and networked manipulation systems. Ramachandran et al.[3] also try to realize the nano manipulation using AFM but they are focused mostly on automatic manipulation systems.

In this paper, user interface issue for the Tele-Nanorobotics system [11] which has the aim of user-friendly manipulation of nano scale objects connecting AFM and tele-robotics technology.

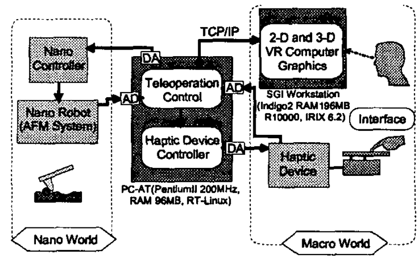


Fig. 1. Tele-Nanorobotics system setup.

II. System

A. System Setup

The overall setup of the Tele-Nanorobotics system is shown in Figure 1. In this system, AFM is used as the nano manipulator and force and 3-D topology sensor, and the haptic and the graphical interfaces are used for the representation of the nano world to the user in real-time. The PC with RT-Linux operating system is used for the teleoperation control between the nano and macro world, and Ethernet interface with 10 Mbps speed is utilized for the data transmission.

B. AFM

AFM has a flexible (like a micro-spring) cantilever with the very sharp tip at the end which has a radius size around $20nm$. The tip or sample is positioned with nanometer or Angstrom resolution in a very close proximity or measuring the tip-sample interatomic interaction forces. When approaching to the sample surface, the tip is bent by the repulsive force between the sample and the tip. Assuming the cantilever is in equilibrium, this force F is calculated by using the equation: $F = k_c\zeta$, where ζ is the deflection and k_c is the spring constant of the AFM tip. The shape of the sample surface can be measured by keeping the force value constant and controlling the Z position while scanning the sample. As the AFM hardware, we used our home-made AFM [12].

AFM is conventionally used for the 3-D topology measurement, but it can also be assumed to be a simple manipulator where its tip is assumed to be a simple pushing or cutting gripper. Thus AFM is taken as the slave device of the teleoperation control system.

III. Interface System

A. Operation Mode

Operator has two initial steps for the manipulation. At first: scanning the sample, getting the surface topology data, and watching the graphics which show the nano world. Secondly: feeling, touching and deforming the nano world, and moving the nano object using the 3-D shaded graphics visual display and force feedback device. The first step is called as the *Visualization Mode* which is the same as the general AFM imaging, and the second one is called as the *Operation Mode* which enables the interaction with the nano world.

In the Visualization Mode, basically only the visualized graphics is used. The aim is to watch the sample topology not in the real-time but off-line (after the first scanning). The real-time viewing during manipulation is almost not possible since scanning takes time (for example it takes about several minutes to scan the sample with 50×50 points in our system) and the tip is utilized for only manipulation or only imaging at one time. After acquiring the data of the sample by this mode, the operator shifts to the Operation mode. Next to manipulation, the region of manipulated parts are scanned again, and the new configuration is updated.

B. Visual Interface

B.1 Necessity of Visualization

Visual sensing is the most important sensing for us during our daily lives for interacting with our environement. However, the resolution that human eye can directly detect is limited to 100s of micrometer sizes of objects, and if we also want to interact with larger or smaller objects special tools such as telescopes or microscopes are needed. For the nano manipulation, AFM is a potential tool for getting 3-D topology images of any type of material down to atomic sizes. For presenting these images to the operator for nano manipulation, interactive garphics tools such as Virtual Reality graphics technology is promising. Almost 3-D graphics with the arranged view direction, zooming scale, orientation, and etc. by the operator is achieved by this way. But this kind of image displaying, the position and force graphics of the AFM tip (manipulator) should be shown in real-time in the same graphics for an intuitive manipulation. Thus, nano manipulation visual displays must differ from commercial image display package softwares.

B.2 Nano Visulator

Nano Visulator provides the Virtual Reality 3-D graphics of the AFM topology image and AFM tip position in real-time. As shown in Figure 2, AFM gets the height data z at each Δx, Δy steps during scanning the sample along xy-axes. At each $(i\Delta x, j\Delta y)$ point, the position vector r_{ij} is held as follows:

$$r_{ij} = (i\Delta x, j\Delta y, z_{ij}) \qquad (1)$$

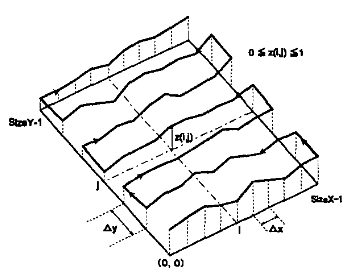


Fig. 2. Scanning direction of the AFM and the acquired data.

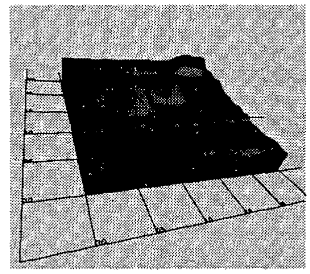


Fig. 3. Nano Visulator gaphics example for 0.5 μm Si particles on a Si substrate with range of 5 x 5 μm^2 and resolution 100 x 100. AFM tip (spherical ball), easy-to-observe helping lines of x-y sample lines corresponding to the tip position, and x-y scale rulers are also helpful during manipulation.

where $i = 0, \ldots, (SizeX - 1)$ and $j = 0, \ldots, (SizeY - 1)$, $SizeX$ and $SizeY$ are the maximum scanning sizes along x and y-axes respectively, and z_{ij} is the sample height at $(i\Delta x, j\Delta y)$. Δx and Δy are normally taken as the same. Furthermore, $\hat{z}_{ij}$ is normalized in the range such that $\hat{z}_{ij} \in [0, 1]$ by $\hat{z}_{ij} = (z_{ij} - z_{ij}^{min})/(z_{ij}^{max} - z_{ij}^{min})$ where z_{ij}^{max} and z_{ij}^{min} are the maximum and minumum height data respectively.

When transforming the acquired data to the 3D graphics data, the scaling parameters, α_{xy} and α_z along the XY directions and Z direction respectively are calculated as following:

$$\alpha_{xy} = \frac{xy_{range}}{Max\{SizeX\,\Delta x, SizeY\,\Delta y\}} \qquad (2)$$

$$\alpha_z = \frac{z_{range}}{\Delta z} \qquad (3)$$

where $\Delta z = z_{ij}^{max} - z_{ij}^{min}$, xy_{range} and z_{range} are the drawing range corresponding to the graphics coordinates of x-y axis and z-axis respectively, and are initialized as 3.0 and 1.0, then the graphics is drawn in the range 3.0 x 3.0 x 1.0. These values are changable to any value by the operator, thus the magnification and the reduction can be done at the x-y and z-axis independently.

This graphics is drawn by using the OpenGL software library to have the common use on the Silicon Graphics Workstation. The sample surface color, light source position are in accordance with eye position. The example of this graphics is shown in Figure 3, which shows the Si particles with the 0.5 μm size radius on the Si substrate with the sizes 5 x 5 μm^2 by scanning with the 100 x 100 resolution.

C. Haptic Interface

After visual sensing, tactile sensing is one of the other important information for us during realizing dexterous manipulation tasks. Since AFM can measure the interatomic forces in real-time, this information can be scaled to the macro world using a bilateral teleoperation control system [14] via a haptic device for easily performing dexterous manipulation.

A one degree of freedom (DOF) haptic device[13] as shown in Figure 4 is used for feeling the scaled nano force in the z-axis. The operator puts his/her finger on the arm part, can apply force and feel the scaled nano force through the applied torque of the linear motor in the haptic device which is controlled by a teleoperation controller.

D. x-y Motion

Present haptic device cannot control the tip position in the x-y axis. Therefore the conventional mouse is used for the x-y motion commands. The tip x-y motion reference commands are determined by moving the mouse on the surface in the Nano Visulator graphics. These reference commands are sent to the PC using the TCP/IP interface, and the x-y stage is controlled for tracking these values. However, there may be positioning errors due to the stage actuator properties and environmental disturbances, the real x-y position is measured using LVDT (Linear Variable Differential Transformer) sensors at each axis. The real positions are sent back to the graphics environemnt using TCP/IP, and the real position of the tip is updated.

IV. Nano World and Manipulation Problem

A. Nano World

The gravity which is dominant in the macro world becomes negligible in the micro/nano world with respect to the sticking forces of the van der Waals, capillary or electrostatic forces. Therefore, nano objects can easily stick to the AFM tip, and special design issues related to the manipulation environment, tip and object sizes and material types are proposed to resolve these problems [17].

B. Force–Distance Curve

During approaching to and retracting back on a flat sample by the AFM tip, force-distance relation is measured using the AFM system as given in Figure 5. At the beginning, there is no deflection on the AFM cantilever since there is no force. But coming around 50 nm, van der Waals, capillary and electrostatic forces become to act, and there is a small attractive force peak until to the contact. The contact point is around zero position (0.3 *nm* exactly). After contact, repulsive interatomic forces deflect the cantilever almost linearly. When retracting back, after the contact point, there is still attractive force until to around 200 *nm* distance with a large peak due to the capillary forces (there occurs a liquid meniscus between the tip and water layer such that it breaks after an elatic elongation process). Here, the attractive forces become to act before contact at a limited short range with a fast behaviour. Especially approaching small peak is difficult to measure every time (retraction peak is easy to observe). Thus, force feedback is difficult for the attractive parts.

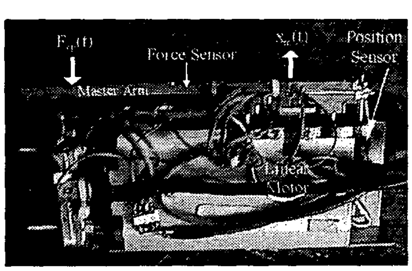


Fig. 4. 1 degree of freedom haptic device

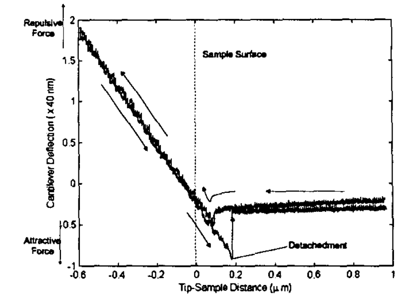


Fig. 5. Force - distance curve : Si sample

C. Manipulation Problems

In the conventional system without the interface, the problems when manipulating the nano world are as follows:

1. Nano world can not be seen in real-time and AFM measurements can contain errors (due to finite tip shape, and etc.),
2. Tip position can not be recognized during manipulation,
3. No device to manipulate,
4. Forces can not be felt.

The problems 1–3 are almost resolved by the development of the interface system mentioned above. Using the haptic device with force feedback along the z-axis cannot solve the Problem 4 completely. This device is not enough for feeling the x-y axis frictional forces. Feeling the force in the x-y axis is the future work.

There are four general items after developing the interface as follows:

1. Attractive force has the influence around the sample surface *even* there is no contact with the objects during manipulation,
2. Length scale becomes down to 10^{-9}, (for example, applying 1 nN force on the 1 nm^2 results in the pressure of 10^9 Pa), thus tip or sample can be easily broken,
3. AFM topology image is not always correct due to the positioning errors, environmental distrubances, nonhomogenous force duistribution on the sample, and finite tip size.
4. Positioning errors should be avoided for precise manipulation by using sensors or extra sensory feedback.

The errors in item 4 are about $\pm 3nm$ in the x-y axis and about $\pm 1nm$ in the z-axis, and these results are the same as item 3.

Item 1 makes controlling the tip difficult and item 2 causes the tip or sample to be easily broken. Item 3 and 4 show that the error always exists in the xyz position between the graphics and the real nano world. This position error may result in undesirable tip-sample contact that can damage the tip or sample. Therefore, accurate positioning of the tip along the z-axis on the sample is important. Then, experiments have been conducted for understanding what are the necessary functions of the interface for preventing the position error in the z-axis.

V. Experiments

One of the most frequent movement during manipulation is the position control in the z-axis. Considering the task of pushing the objects as shown in the Fig. 6, the aim of the experiment is approaching the tip to the sample surface without breaking.

A VR Nano Simulator is constructed for conducting simulated experiments for the z-axis contact approach. Thus, different situations such as different type of materials and environmental parameters are easily changable, and the operator can experience the approach task by this interface prior to the real experiments.

A. Virtual Nano Simulator

The aim of this simulator is to predict the change of the nano world by the operator, to help the operator consider the strategy of the manipulation, and to visualize the virtual movement in the nano world during manipulation.

B. Force Model

The two models are used for the z-axis, assuming that the cantilever tip is a sphere and the sample surface is a flat plane. In the non-contact region, the Lennard-Jones model is used and JKR model [15] in the contact region. Many other simulation researches use the Hertz model which does not include the adhesion force [16], and few research uses the graphical interface for the operator.

In the non-contact region, the force from the sample is the function of the distance between the tip and the sample, and is represented as follows:

$$F_z = -\frac{AR_c}{6\sigma^2}\left(\frac{\sigma^2}{h^2} - \frac{\sigma^8}{30h^8}\right)(\text{when } h \ge a_0) \qquad (4)$$

where h is the distance between the sample and the tip (upper is plus), a_0 is the contact point (where the force is 0) and $a_0 = 30^{-\frac{1}{6}\sigma}$. A is the Hamacker Constant which determine the Van der Waals force, R_c is the radius of the cantilever tip, and σ is the atomic distance.

In the contact region, the influence of the adhesion force appears and contact radius has also relationship with this force. The force F_z from the sample is following:

$$F_z = k_c\zeta \qquad (5)$$

Where ζ is the deflection of the tip. The contact radius a when applying the force to the sample with this force is

$$a^3 = \frac{R_c}{K_0}\{F_z + 6\pi R_c\gamma + \sqrt{12\pi R_c\gamma F_z + (6\pi R_c\gamma)^2}\} \qquad (6)$$

where $\frac{1}{K_0} = \frac{1-\nu_t^2}{E_t} + \frac{1-\nu_s^2}{E_s}$. And ν is the Poisson coefficient, E is the Young Modulus. t shows the cantilever tip and s shows sample.

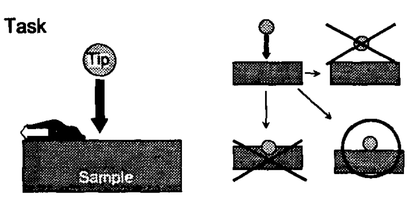


Fig. 6. Experiment task

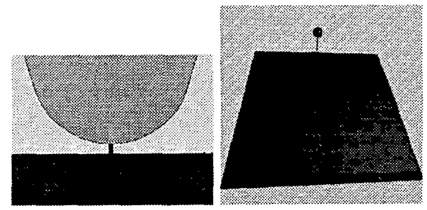


Fig. 7. Graphics interface using for experiments 2D with force arrow (left) and 3D (right)

$R_c[nm]$	20.0	ν_t	0.5
A	1.3×10^{-19}	$\sigma[\AA]$	3.49
$E_t[GPa]$	179	γ	0.071

TABLE I

PARAMETERS FOR THE SIMULATOR IN EXPERIMENTS.

The distance δ from the sample when contact by the adhesion force is calculated by this radius a as

$$\delta = \frac{a^2}{R_c}\{1 - \frac{2}{3}(\frac{a_c}{a})^{\frac{3}{2}}\} \qquad (7)$$

where $a_c = (\frac{12\pi(R_c)^2\gamma}{K_0})^{\frac{1}{3}}$ is the contact radius when $F = 0(h = a_0)$ for the JKR model.

The displacement will occur, when the contact radius becomes less than $a_s = \sqrt[3]{4}a_c = 0.603a_c$.

C. Experimental Conditions

The two condition is prepared in the experiments: one without the position error, second with the position error. Four type of interfaces are investigated:

① Only force feedback by the haptic device,
② Force feedback + 2D side view graphics,
③ Force feedback + 3D graphics,
④ Force feedback + 2D side view graphics + graphics presentation of the force value.

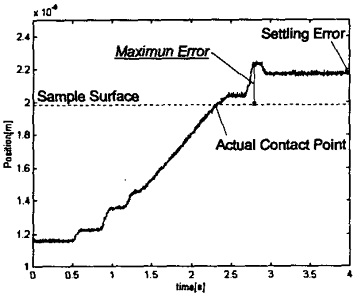
The graphics images of the 2D and 3D are shown in the Figure 7. Diffirent materials with different softness values (Yaung Modulus) have been selected as soft, medium and hard samples.

The parameters for the Nano Simulator is shown in Table I. The parameters of the sample are hard (Si:$E_s = 179GPa, \nu_s = 0.5$), middle (graphite:$E_s = 10.7GPa, \nu_s = 0.3$), soft (chromosome:$E_s = 0.18GPa, \nu_s = 0.3$). And the tip is made of Si. The initial position of the tip is $20nm$ height from the surface, the position and the force scaling factors are $S_p = 2 \times 10^{-8}, S_f = 2 \times 10^5$, respectively. The position scaling factor is determined by considering that the moving range of the device is $2cm$ and the resolution is $0.01cm$. The resolution in the nano world is $0.01cm \times S_p = 0.2nm$ with this parameter. And the force scaling parameter is the value calibrated for the manipulation.

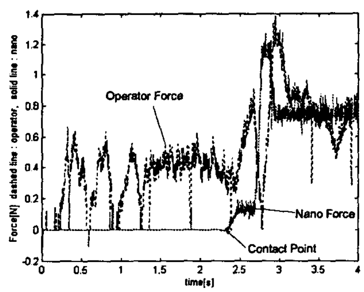
In the experiment with the position error, the graphics has randomly $\pm 3nm$ position error, which is not shown to the operator. And the experiment with only the force feedback has not been done.

D. Experimental Results

According to the results, the maximum error which shows how deep the tip indented into the sample surface



(a)[Time vs. Position]



(b)[Time vs. Force(Operator:Dotted Line, Nano World:Solid Line)]

Fig. 8. Typical result (hard sample, only haptic device)

	①	②	③	④
Soft	18.56	2.77	1.34	1.27
Middle	10.63	0.68	0.60	0.83
Hard	3.26	1.45	0.98	1.03

TABLE II

MAXIMUM ERROR [NM] (WITHOUT POSITION ERROR)

is small. The typical change of the force and the position is shown in Fig. 8. This experimental trial number is 10 and the means of the maximum error shown in the position graph of Fig. 8 are shown in Table II and III, and in Fig. 9 and 10. In Figure 10, experiments are conducted with position error, and only force feedback case is shown as for reference.

E. Discussions

E.1 Without Position Error

Comparison with Interface Comparing ① with ② ~④, visual graphics can realize better position control even if the force feedback is not enough for the soft samples. ③ and ④ has the good results. The operator can get the two means to execute the task: not only adjusting the position of the tip in the graphics but also adjusting the representation of the applied force, and can control the position better.

	②	③	④
Soft	3.91	1.54	2.43
Middle	1.57	0.88	1.99
Hard	1.25	0.82	1.31

TABLE III

MAXIMUM ERROR [NM] (WITH POSITION ERROR)

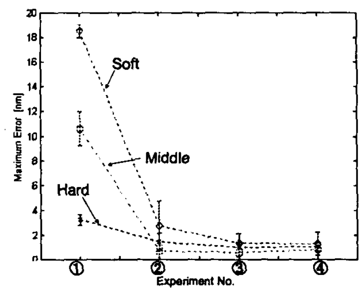


Fig. 9. Maximum Error (without position error) : Exp. No. vs. Error

The result of ④ is better than ②, because, by the observation of the experiments, the operator can recognize the position error with the side view graphics and tries to adjust the position with more accuracy. Also the experiment sometimes results making the big error with miss-operation (case ②). The similar occasions are observed in the results that the middle sample is better than the hard one. In the case of the middle sample, the operator can not feel the enough force, but, in the case of the hard sample, the operator tries to adjust the position and the tip is contacted to the sample, and he feels the big force and can not control the tip position easily.

E.2 With Position Error

The case with the graphics feedback is better than the case without the graphics, but the maximum error tends to be bigger than the case without the position error because the graphics is not accurate. And the judgement is more important in this experiment, thus ③ is the best result. Therefore, the force feedback, especially the representation of the force value, is important in the nano manipulation since the graphics information is not accurate.

VI. CONCLUSION: NECESSITY CHARACTERISTICS AND FUNCTIONS

The necessary characteristics for nano manipulation are as follows:

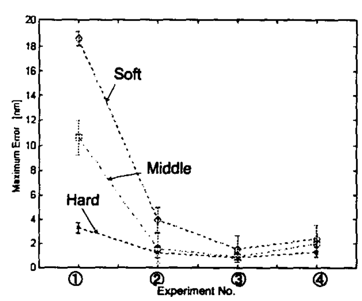


Fig. 10. Maximum Error (with position error) : Exp. No. vs. Error

A. Graphical Interface

Necessary information to be shown in the graphics interface is the tip position and the magnitude of the force applied to the tip. Also considering the judgement of the contact, 2D side view graphics is better for the contact since the depth is felt easily. The 3D graphics, however, is necessary for the manipulation, then the 2D graphics should be prepared at the same time for the position control of the contact or the movement in the z-axis.

B. Haptic Interface

The structure which has the wide moving range is necessary in order to control the position precisely. The device using for these experiments has only $2cm$ moving range, then the more precise control is difficult. The ideal moving range is at least 4–$5cm$ by considering that the manipulation is done by the finger with the wrist fixed. The device with the movement in the x-y axis is necessary. The mode, however, that the only one movement is possible is necessary by the difficulty of the z-axis position control. The movement range in the x-y axis which is the same as the one of the mouse is enough in these experiments. Then about $20 \times 20cm^2$ range should be suitable. Moreover, the structure which can be good for feeling the attractive adhesion force peculiar to the nano world is also necessary.

C. Control

The request to the control from the interface is to set the scaling parameter value by which the operator can feel the force to be neither too hard nor too soft. As the vibration would be occurred around the surface if the sample is too hard and the force can not be felt if the sample is too soft. The difference of the force value between when the sample is hard and when is soft is about 100 times, thus the suitable force scaling parameter setting is difficult. But, only in the case of the contact detection, the parameter should be set to the value that the operator can feel the adhesion force and the relative softness is kept after the contact. In this case, the stability of the control system is necessary in the whole design.

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