Nano Tele-Manipulation Using Virtual Reality Interface

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Abstract — A telemanipulation system from macroscale world to nanoscale world with a user-friendly virtual reality-based human-machine interface has been proposed in this paper. This paper focuses on the direct telemanipulation of nano objects with sizes $1nm - 1\mu m$. A home-made AFM device has been utilized as the nano vision and force sensor as well as the nano manipulator. As the teleoperation interface, a force-feedback device and 3-D virtual reality graphics visualization environment have been constructed. Preliminary simulation and experimental results are presented.

1 Introduction

By the invention of the Scanning Tunneling Microscope (STM) and Atomic Force Microscope (AFM), a new era for the nanometric scale science and technology especially for the nanotechnology studies has been started. Microelectromechanical systems with their recent exciting improvements can replace its place with the nanoelectromechanical systems in the near future. But, such a trend neccesitates nano manipulation and fabrication technologies besides of nano imaging where such technologies are in the very early stage. There have been few studies on the nano manipulation field while it attracts more and more attention recently by increasing necessity for such a technology.

Nano manipulation system examples in the literature utilizing knowledge from the macrorobotic manipulation and assembly with the physics and chemistry of nanoscale phenomena are the systems introduced in [4], [7], [2]. Hollis et al. [4] utilized STM as the nano manipulator where they used the Magic Wrist as the haptic device for nano force sensing. Falvo et al. [2] and Junno et al. [5] used AFM as the nano manipulator. In all of the nano manipulation systems except [2] there is no teleoperation or direct control of the operator. They mostly realize the nano manipulation task by trial and error.

In this study, AFM is selected to be the nano manipulator as well as the nano imaging device. The principles of operation of the AFM is shown in Figure 1. The typical basic components are the cantilever with a very sharp prismatic tip, nano positioning system, sample to be imaged, and deflection detection system. The interatomic forces between the cantilever tip and the surface atoms result in an attractive or repulsive force depending on the separation distance between the tip and sample. Placing the tip around several nanometers on the sample create an attractive force where a distance less than around 0.3 nm result in a repulsive force. Thus, in the case of the mode called 'contact' mode, selecting a constant force/height reference, the sample or the tip is moved on a point of the sample until getting the constant force/height value. The height data giving the constant value is assumed to be giving the height information of the sample surface implicitly or explicitly, and scanning all surface this way gives the 3-D topology image of the surface. AFM can be used for imaging of any material conducting or nonconducting while STM can be used only for conducting materials.

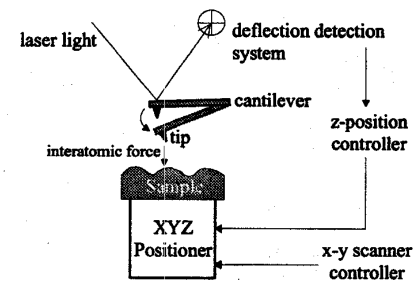

Figure 1: Basic structure of an Atomic Force Microscope.

Using AFM cantilever tip as a 3-DOF (X-Y-Z motion) robot, simple pull and push tasks can be realized. By this kind of tasks 2-D assembly of nano particles or biological object manipulation can be possible. For this reason, analytical and experimental models of the AFM cantilever dynamics and nano forces acting during the manipulation are introduced in this study. Van der Waals, surface tension and electrostatic forces are dominant in the nano world where gravity is negligible. Moreover, at the tip-sample distances around 0.3 nm, these forces become quantum mechanical or electromechanical forces, and chemical interactions also play a very important role. At this point, an interdisciplinary research is essential among computer scientists, physicists, chemists, biologists and material scientists.

2 System Setup

The setup of the telemanipulation system is shown in 2. In the macro world, an operator tries to manipulate nanometric objects while seeing them in real-time by using a 3-D virtual reality graphics environment and feeling the existing forces in the nano world by a haptic device. That haptic device is simultaneously utilized as the master manipulator for generating command signals for the nano/slave manipulator. A teleoperation control scheme provides necessary reference commands for the slave by recieving the master signals. Slave controller generates necessary inputs and the slave manipulator moves accordingly using micro actuators such as piezoelectric actuators. In this study, AFM cantilever is selected as the slave/nano manipulator which is the nanometric force and position sensor at the same time. By these features, AFM is a unique candidate for a nano manipulator, but this kind of usage is very new in the

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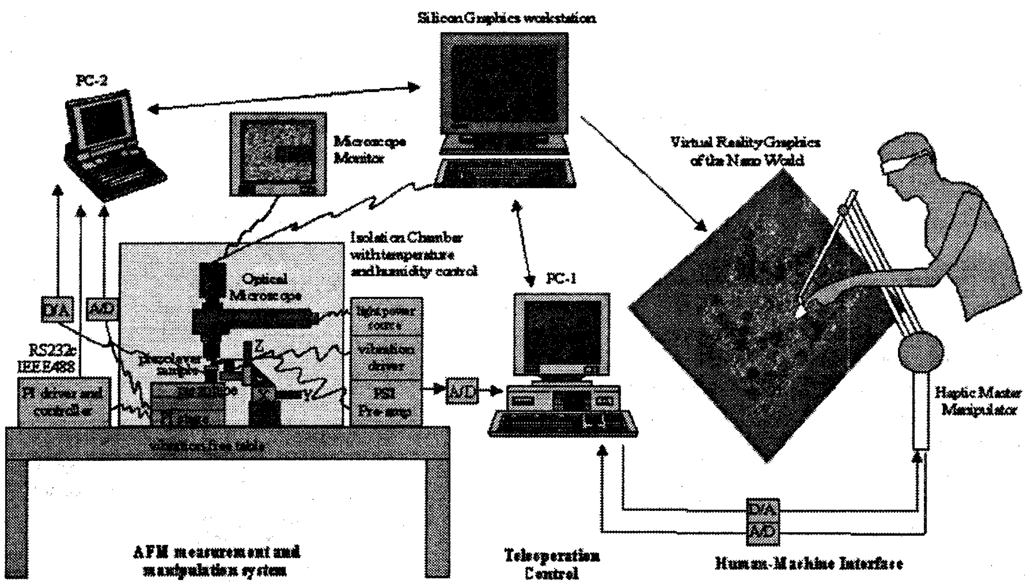

Figure 2: The tele-manipulation system setup.

literature [10] and not well-understood. AFM cantilever provides 3-D topology and interatomic force feedback in real-time to the user interface. By this way, user-interface system puts the scientists *on* the nano world, *in* control, *while* the experiment is happening, thus turning the AFM from a remote device into a real-time, user-guided device.

Beginning from nano, and going through to the macro world, the main issues are as follows:

- *nano world:* understanding micro/nano physics, nanometric object properties, nano force and position sensing, instrumentation, and nano manipulator,
- *macro world:* user-friendly user interface utilizing virtual reality (VR) technology and force feedback devices,
- *macro to nano (M2N) world:* teleoperation control, and scaling.

3 Nano World

3.1 Nano Physics

For enabling reliable nano manipulation, nano forces acting during manipulation should be understood well by analytical and experimental models. For understanding micro/nano physics, there are two main approaches in the literature: *heuristic* and *model-based* approaches. The former [9] tries to learn parameters that affect the micro/nano forces by trial and error experimenting, or introducing simple heuristic rules. The latter group tries to analyze the forces in simulation environments (i.e. Molecular Dynamics simulations) by changing different parameters, and then compare the validity of their models with the experimental results. We propose to synthesize both approaches such that teleoperation force testing experiments will be done while the analytical models are being prepared at the same time.

One of the most important phenomenon in the nano world is the sticking effect. There are three main forces responsible from sticking considering only microscopic object interactions: Van der Waals, capillary and electrostatic forces. Van der Waals force is a long-range force, and exists in every material such as gravity, and is due to instantenous dipole moment changes of atoms and has types of dispersion, induction or orientation. Work function for different two object interactions are shown in Figure 3 where force can be computed from $F_{vdw} = -\frac{\partial W}{\partial z}$. A is defined to be the Hamacker constant ($0.4 \times 10^{-19} J < A < 4 \times 10^{-19} J$ for all materials). From the equations, it can be seen that F_{vdw} depends on the material type (A), geometry, roughness of the surface, and distance between two objects z. Also, due to the retardation affect it is almost negligible if $z > 100nm$.

Capillary force or surface energy is caused by the liquid layer on the objects such as water layer due to humidity. It is approximately given as

$$F_{cap} = 4\pi R\gamma \quad (1)$$

between a sphere with radius R and liquid with surface energy constant γ (for water $\gamma = 73 \times 10^{-3} N/m$). γ is approximately $\simeq 20mJ/m^2$ for many liquids and solids, and it is related to the Hamacker constant A as $\gamma \simeq 5.92x10^{17} A/Area$. F_{cap} depends on the geometry of the objects, separation distance and liquid type.

Electrostatic or roughly Couloumb forces such as $F_{es} = Q_1 Q_2/(4\pi\epsilon_0\epsilon r^2)$ can exist in contact or noncontact cases. Depends on the charge densities of the surfaces or the charges of the particles in noncontact. But, in contact case, it becomes very complicated because, there are many sources of electrification such as triboelectrification (charge exchange during friction), or contact electrification (charge exchange). Also, depending on the material type as conductor, semi-conductor or conductor its analysis changes very much which makes also its modeling difficult.

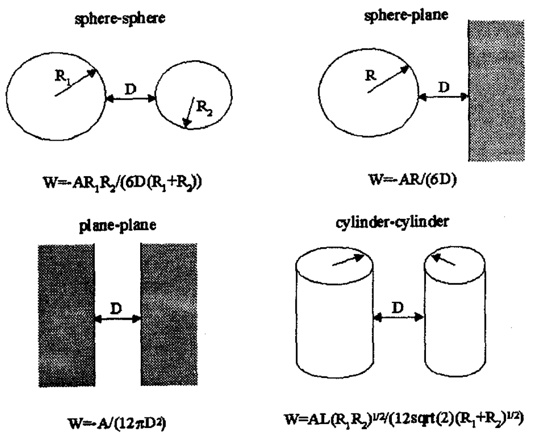

Figure 3: Van der Waals potential functions for different object interactions.

As simulations of these forces, first F_{vdw} between a Si spherical tip probe and mica plane sample in vacuum and water environments. As can be seen from the Figure 4, in water F_{vdw} increases. Also comparing F_{vdw} in water with F_{cap}, Figure 5 shows that F_{cap} is dominant. On the other hand, if F_{es} exists, it is generally bigger than both of them. Thus, for avoiding unstable sticking effects, humidity, charge on the probe or sample, specific geometries should be avoided.

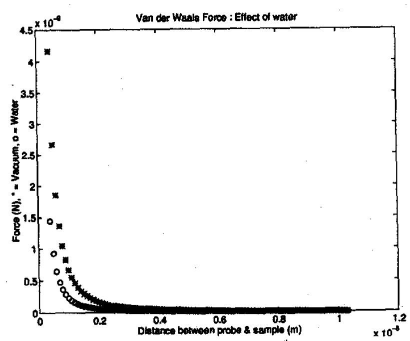

Figure 4: F_{vdw} in vacuum (o) and in water (*) for Si probe and mica plane case.

3.2 AFM as the Nano Sensor and Manipulator

A specific AFM cantilever from PSI Co. is used for nano imaging and manipulation as can be seen in Figure 6. It is a Si cantilever that exhibit piezoresistive effect [13] such that when the cantilever is stressed by any external force

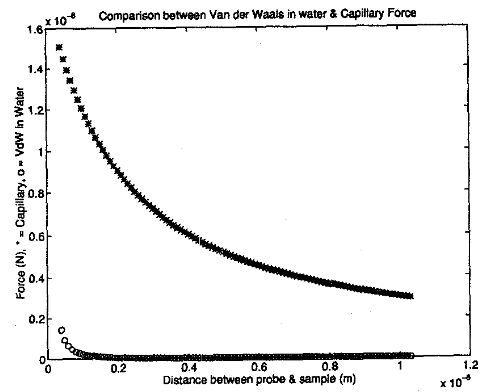

Figure 5: F_{vdw} in water (o) and F_{cap} (*).

the resistance of the cantilever changes. Thus, using a dc-biased Wheatstone bridge, the change of the resistance can be converted into a voltage change which can directly proportional to the deflection [3].
Modeling of the cantilever is essential for controlling its deflection. Cantilever can be modeled as a simple mass-spring system as shown in Figure 7 with mass m_c, damping b_c, and stiffness k_c such that

$$m_c\ddot{\zeta} + b_c\dot{\zeta} + k_c\zeta = F_n(\zeta, g), \qquad (2)$$

where ζ is the cantilever deflection from the rest position, AFM cantilever has a very sharp tip with radius R_c that interacts with the sample atoms and resulting attractive or repulsive atomic interaction force F_n (force normal to the cantilever tip) deflects the cantilever. By moving the sample or the cantilever this deflection amount can be controlled and, for example, by getting a constant deflection control (constant-force mode), the height information of the sample is directly related to the amount of movement g. Scanning all of the surface provides the 3-D topology image.

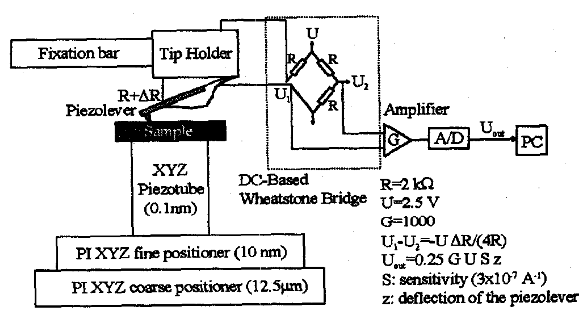

Figure 6: AFM with piezoresistive cantilever and electronic detection system.

$F_n(\zeta, g) = F_n(h)$, where $h(t) = z_0 - g(t) + \zeta(t)$ is the distance between the tip and the sample surface at time t, is a highly nonlinear function, and following model is used for estimating this tip-sample interaction force:

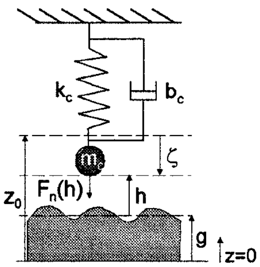

Figure 7: AFM cantilever model as a mass-spring system.

$$F_n(h) = \begin{cases} F_0\left(\frac{\sigma^2}{h^2} - \frac{\sigma^8}{30h^8}\right), & \text{if } h > a_0; \\ -\frac{AR_c}{6a_0^2} + \frac{8}{3}\frac{E\sqrt{R_c}}{1-\nu^2}(a_0 - h)^{3/2}, & \text{if } h \leq a_0, \end{cases} \quad (3)$$

where a_0 the interatomic distance, $F_0 = \frac{-AR_c}{6\sigma^2}$, E the Young's modulus, and ν Poisson's coefficient of the sample. $h > a_0$ condition means noncontact region, and the other is the contact region. In the noncontact part, phenomenological Lennard-Jones model [8], and for the other, the summation of attractive Van der Waals force and repulsive indentation force derived from Hertz's model [12] are approximated. But, in the contact region there are other forces such as adhesion, friction, and triboelectrification forces that are not included in the above model. Especially, large lateral forces are important during contact manipulation since it can cause instabilities.

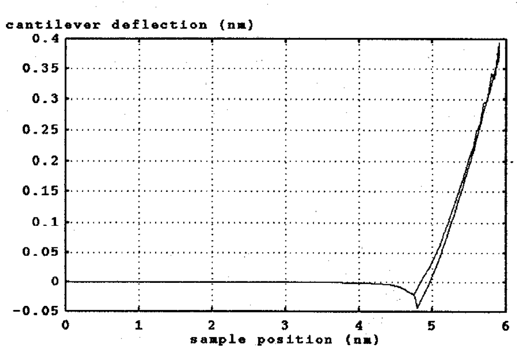

Figure 8: Deflection-distance relation during the tip and sample approach (simulation).

Using this model, the approach of a cantilever tip to a sample surface is simulated, and the F_n vs. g curve is shown in Figure 8. The parameters are $k_c = 8N/m$, $f_r(resonantfreq.) = 150KHz$, $R_c = 25nm$, $E = 0.2GPa$, $\nu = 0.3$, $\sigma = 3.49A^o$, $S_c = 1 \times 10^{-6}/nm$, $A = 1 \times 10^{-14}J$. The (-) force means the attractive and (+) do repulsive forces. Force is zero at the contact point, and it is attractive before this point, and repulsive after. It is seen that F_n-g relation becomes approximately linear in the repulsive region.

4 Macro World

4.1 Virtual Reality 3-D Visualization Interface

The first main important tool for the user is real-time and interactive visual feedback from the nano world. Since AFM can measure the 3-D topology of any sample (conducting or nonconducting), this information should be presented to the user in a friendly way. Conventionally, AFM data are presented off-line or on-line as 2-D intensity images as shown in Figure 9. However, virtual reality (VR) graphics technology has been used in this study for generating sample images in on-line and 3-D space.
AFM provides $\mathbf{r}_{ij} = (i\Delta x, j\Delta y, z_{ij})$ topology data at (i,j) point on the sample where $i = 0,\ldots,S_x - 1$ and $j = 0,\ldots,S_y - 1$, Δx and Δy are $x - y$ scanning steps where usually $\Delta x = \Delta y = \Delta$, and S_x and S_y stands for the x and y direction scanning grid size. Assuming that (i,j) points are directly transfered to the computer screen origin as pixel points by shifting such as

$$(i,j) \rightarrow (i - (int)(S_x/2), j - (int)(S_y/2)), \quad (4)$$

z_{ij} is transformed as

$$z_{ij} \rightarrow z_{ij}/\Delta * scale_z, \quad (5)$$

where $scale_z$ can be determined by the user.
After transforming to the screen coordinates, the image is transformed (having 3-D perspective) again using OpenGL software functions in order to have the 3-D feeling. Here, rotation in x and y axes and zooming in z direction features are included in the graphics software that can be changed by mouse or the haptic device on-line interactively. Thus, user can see any specific local region on the surface in detail, even the backside of the 3-D image. En example of such 3-D images is shown in Figure 10. This image can be directly transformed to stereo images by using Silicon Graphics workstation graphics cards, and can be presented in 3-D to the user using a stereo glass, or a head mounted display.

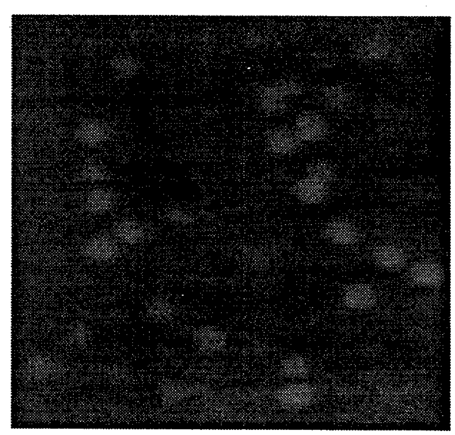

Figure 9: Conventional 2-D greyscale AFM image.

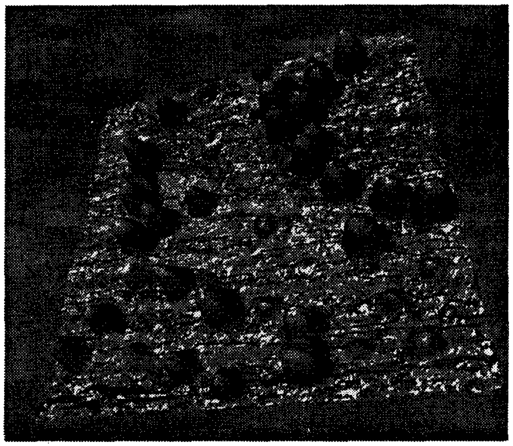

Figure 10: Our 3-D virtual reality graphics image of InAs dots around 10 nm radius with an sample size of $150 \times 150nm^2$.

4.2 Force Feedback Device

The second issue of the user interface is the haptic interface where the nanometric forces in the order of nN should be sensed on the operator hand for a reliable teleoperation. A haptic device constructed before in Hashimoto Laboratory called Hand Shake Device [6] has been adapted as the nano force feedback and master devices. The resulting VR visualization and haptic interface system photo is shown in Figure 11. The details of the device is explained in [11].

5 Macro to Nano World

5.1 Scaling

The position and force information in the nano world is in the order of nm and nN respectively while cm and N in the macro world. Then, a scaling law is required for information transformation from both sites. Before introducing the scaling approach the similarity between two worlds should be defined. There are three similarity approaches: *geometrical* similarity (all length scale ratios are the same), *kinematic* similarity (length and time scale ratios are the same), and *dynamic* similarity (length, time and force scale ratios are the same). In the context of nano manipulation, it may sometimes be desirable to scale forces contributed by various physical effects (e.g., inertia, stiffness, friction) independently. For example, depending on the task, inertial forces may be scaled in a grater extent than surface tension forces which make a nanodynamical system feel like a macromechanical system. In the AFM force feedback case, the measured force is always proportional to the cantilever spring constant k_c in the static case which means we measure a spring force every time. Then, dynamical similarity can also be used in this case. But, in the dynamic mode (oscillating the tip or the sample in the resonance frequency) damping and inertia kind of forces also act and kinematic similarity can be better. For the static case, the geometrical scaling factor S_x is computed depending on the range and scale that cantilever deflects and master device move, and the same for the force scaling factor S_f.

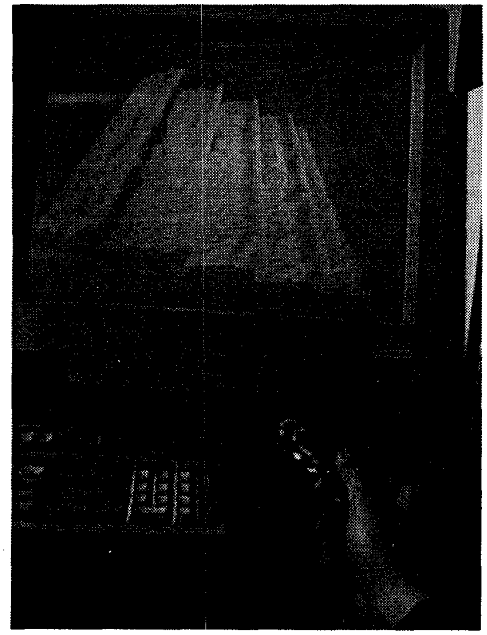

Figure 11: VR visualization and haptic device setup.

5.2 Teleoperation System

The basic structure of the teleoperation control system is shown in Figure 12. These kinds of systems are called bilateral impedance control systems where Virtual Impedance (VI) is used for generating reference inputs x_{mr} and x_{sr} (master and slave reference positions) for master and slave controllers by imposing an artificial impedance on the environment. Basic advantages of VI are as follows:

- it can avoid the large impedance generated by master-slave systems,
- it filters out the force high frequency components since it behaves as a second order low-pass filter transforming force into displacement.

VI is a target virtual mass-spring system with mass M_v, stiffness K_v, viscosity B_v, and dynamics as:

$$F_o - F_n = M_v\ddot{x}_m + B_v\dot{x}_m + K_vx_m. \quad (6)$$

F_o and F_n represent operator and the nano force measurements respectively.
Impedance shaping, i.e. VI, is an approach to bilateral manipulation, but is not a design methodology. It lacks a general approach to performance specification [1] (this depends on the task at hand and what measure of performance is to be optimized). However, a design methodology incorporating VI is very feasible.
The block diagram of the bilateral teleoperation system is shown in Figure 14. The aim of the control is: as $t \to \infty$, $F_{op} \to S_fF_n$ and $S_xx_m \to x_s$. The master and slave dynamics are given in [11]. Problem here is to select VI parameters K_v, B_v and M_v such that the system is stable and robust depending on the task. As the experiment, the

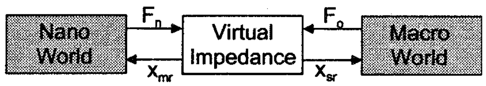

Figure 12: The basic structure of the teleoperation control system.

reference cantilever deflections (between -0.05 nm and 0.9 nm) are computed from the F_n models in the simulation environment, and sent to the master controller as refrence positions by scaling factor of $S_p = 10^9$ and shifting 0.5 cm. These refrence positions during tip-sample approach are shown in Figure 13. Resulting master device positions are also can be seen in the figure. The deflections are exactly felt on the operator hand.

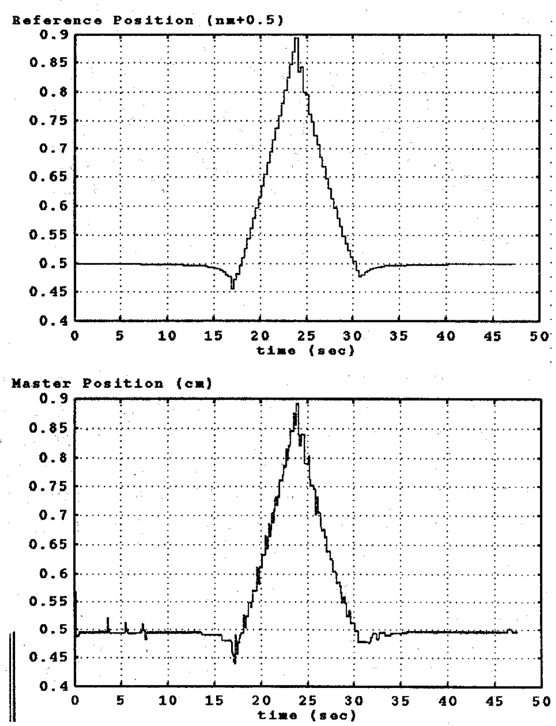

Figure 13: Reference deflection position during the tip and sample approach (simulation), and master device position (experimental).

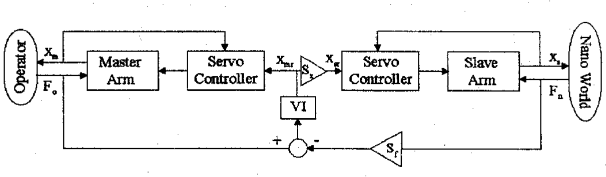

Figure 14: Bilateral teleoperation system using VI model.

6 Conclusion

In this study, a teleoperation system from macro to nanoscale world called M2NT-m system has been proposed and preliminary results are shown. Virtual reality graphics visualization interface has been constructed and experimental images are tested. Extension of the system to 3-D viewing is straightforward by using stereo glasses and stereo graphics image generation. Future work for this part is to extend the system to the on-line 3-D visualization. As the haptic and master device 1DOF linear motor based manipulator with position and force sensory feedback is utilized. Its performance is tested for force sensation. AFM using piezoresistive cantilevers has been constructed and force-distance experiments are realized. Also, models of the cantilever, and the nano forces are constructed. Imaging of the samples with contact mode will be possible in the new future, and some applications can be held. The first goal experiment is to manipulate nano particles using the AFM cantilever with force-feedback teleoperation. As the task, particles can be pushed and pulled on a flat surface and specific structures such as lines, circles, etc. can be constructed in 2-D. These kind of structures are important for understanding the chemical, electrical and mechanical properties of specific materials, and can enable assembly of nano devices in 2-D.

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