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Teleoperated Nano Scale Object Manipulation

Metin Sitti and Hideki Hashimoto

Institute of Industrial Science, University of Tokyo,
Roppongi, 7-22-1, Minato-ku, Tokyo, 106-8558
{sitti,hideki}@vss.iis.u-tokyo.ac.jp

Abstract. In this paper, a teleoperated nano scale object manipulation system is proposed, and requirements of such systems are defined. The system consists of a user interface utilizing visual and haptic displays (macro world), nano-manipulator, controller and sensors (nano world), and teleoperation control and rough to fine imaging and actuation tools (between macro and nano worlds). A home-made Atomic Force Microscope is constructed for nano sensing and manipulation, and a home-made 1-DOF haptic device with Virtual Impedance-based bilateral teleoperation control scheme are utilized. Preliminary experiments consisting of nano scale tactile and force feedback while touching to materials, and 2-D assembly of 2.02 μm size latex particles are realized and results are reported.

1 Introduction

In the field of mechatronics, one of the main directions of research is the miniaturization of robots, machines and devices more and more where this new branch is called as *mico/nano mechatronics*. Recent advances in this field enabled milli-robots inside of nuclear plants, milli-surgical robots for minimal invasive surgery, Scanning Probe Microscopy such as Atomic Force Microscopy (AFM) and Scanning Tunneling Microscopy (STM) where the geometrical, electrical, magnetic, etc. kind of properties of materials can be measured down to atomic scale in 3-D, precision positioning down to 0.01 nm resolution, etc. However, still the total sizes of these robots and machines are limited to millimeter or centimeter sizes, and one of the major reasons is the lack of the manipulation and fabrication technologies for the objects with the sizes less than 10 μm. Construction of these technologies at the nanometer scale can enable nanoelectromechanical systems (NEMS) which are the new frontier in miniaturization and can have revolutionary implications in science and technology. NEMS will be extremely small and fast, and have applications in biological systems such as manipulating cells or genes for repairing or understanding mechanisms more clearly, computer industry such as high-density disk/memory storage and miniaturization of integrated circuit components, material science such as fabricating man-made ultrastrong and defectless materials, etc.

One of the main challenging matters for 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. On the other hand, teleoperation systems have the stages of *direct teleoperation*, and *task-based/supervised teleoperation* systems where in the former, an operator directly enters to the control-loop of the nano-manipulator, and in the latter, the operator only sends high-level task commands, and the nano-manipulator realizes the tasks in an autonomous way. The final goal is fully automatic systems which can enable the mass-production of micro/nano robots or machines in the future.

By manipulation we mean using an external force for positioning or assembling objects in 2-D or 3-D, cutting, drilling, twisting, bending, pick-and-place, push and pull kind of tasks. For manipulating nano scale objects different approaches are utilized. They can be classified into two parts as *non-contact* and *contact* manipulation systems. At the former, laser trapping (optical tweezers) or electrostatic or magnetic field forces are utilized. Yamomoto et al. [1] can cut DNA using restriction enzymes on a laser trapped bead, and Stroscio et al. [2] utilized electrical force between STM probe tip and surface atoms for manipulating Xe or Ni atoms. As the contact manipulation, AFM probe tip is utilized for positioning particles [3, 4] or other nano objects such as carbon nanotubes [5] on a substrate by contact pushing or pulling operations. In these studies, only two uses teleoperation depending upon our information. Hollis et al. [6] 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 [7] utilizes commercial AFM and haptic device for real-time haptic display, but they do not have any report on teleoperation control problem.

In this paper, a tele-nanomanipulation system utilizing AFM probe tip as a contact-type manipulator, and at the same time as a 3-D topology and force sensor is introduced. A 1-DOF home-made haptic device with Virtual Impedance teleoperation control enables haptic display while a 3-D Virtual Reality computer graphics system shows the nano world to the user. As different from previous works, this paper reports the general requirements of the teleoperated nano manipulation systems, discusses the teleoperation control problem, and presents 2-D task-based teleoperated manipulation of 2.02 μm latex particles.

As the organization of the paper, at first, requirements of the teleoperated nano manipulation systems are defined. Then, the proposed system with macro, nano and macro to nano world components is explained in detail. Next, preliminary experiments and results with future directions are reported.

2 Requirements of Teleoperated Nano Manipulation Systems

Main structure of a directly teleoperated nano manipulation system can be seen in

Figure 1. In the macro world, an operator sends commands to the nano manipulator controller while feeling the nano manipulator and object interaction through visual and force displays. Nano world consists of the nano manipulator, controller, sensors and physical environment. Between both worlds, teleoperation controller constitutes the interaction bridge.

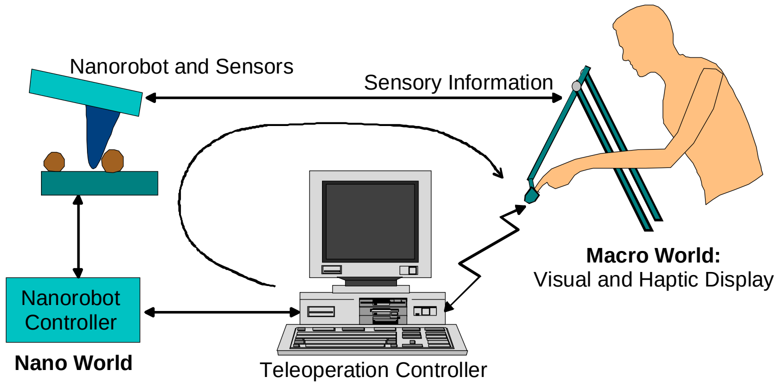

Fig. 1. The structure of a directly teleoperated nano manipulation system.

For a reliable teleoperated nano scale object manipulation using the system in Figure 1, following requirements should be held:

1. Nano World:
   1.1. Real-time force feedback from the nano world is essential. Because, in ambient conditions, only force feedback can be possible for manipulation control since there is no real-time global 3-D vision sensor in the nano world. In vacuum environments, Scanning Electron Microscope (SEM) can give a global 2-D visual information down to 5-7 nm resolution for only conducting and some specific objects, but it is not real-time at the nano scale, and it is 2-D. Secondly, force feedback is required for controlling the interaction force such that the tool is not broken or object is not flipped away where objects become fragile and easily deformable at the nano scale. Furthermore, force measurement can enable recording of forces during manipulation, and then reliable strategies based on force control can be introduced.
   1.2. 3-D visual display of the nano world is required for intuitive manipulation. SPMs can give 3-D topology, electricity, magnetism, etc. images which can be displayed to the operator. However, the imaging sampling time is in the order of seconds or minutes which means on-line imaging is not possible. Moreover, even the sampling time is very fast, since the SPMs are local sensors, and when also SPMs are utilized as the nano manipulator, the on-line imaging of the manipulator-object interaction is impossible physically because there can be one probe at one point at a given time.
   1.3. A nanorobot that can manipulate objects between 1nm-2μm size in 2-D or 3-D in any environment such as air, liquid or vacuum is required. The gripper size of the nanorobot should be in the order of the object to be manipulated.

1.4. Understanding nano forces and nanorobot dynamics is indispensable for reliable manipulation strategies. Therefore, forces and dynamics should be modeled by combining the analytical models with experimental results.
1.5. Nanorobot position controller should have the accuracy at least in the order of $1/10^{th}$ of the minimum nano object part size to be observed.
2. Macro World:
2.1. A user friendly human-machine interface with 3-D interactive graphics display and real-time force feedback enables easy, flexible and safe operation.
3. Macro to Nano (M2N) World:
3.1. A bilateral teleoperation control system is needed for haptic device motion commands transmission to the nano controller, and nano force feedback commands to the haptic device taking the scaling effect into account. Selection of the proper scaling algorithm is challenging. During the teleoperation control, also bandwidth differences of the haptic device and nano controller should be compensated. Furthermore, the stability and robustness of the teleoperation controller should be checked where the nano robot-object interactions, and nano actuators are mostly nonlinear.
3.2. Micro scale imaging (Optical Microscope down to submicron resolution) and positioning (rough to fine methodology) simplifies reaching to the nano scale gradually through micro scale.

3 Nano World

For satisfying the nano world requirements, from SPMs, AFM probe is selected as the nanorobot and force and topology sensor. Because, it enables 3-D atomic resolution imaging and real-time force feedback for *any* material in *any* environment, and can be utilized as a simple contact push and pull manipulator with probe tip sizes down to 10s of nm.

3.1 AFM as the Nano Manipulator and Sensor

Basic structure of a conventional AFM is given in Figure 2. A microfabricated Si cantilever/probe with a very sharp tip at the end, and measured stiffness and geometrical properties can be deflected due to the interatomic forces if the probe tip is positioned very close to a material surface in the order of few nm or Angstrom (A^o) where a standard nano force-distance relation during the tip-surface approach and retraction is shown in Figure 3. When approaching there is a nonlinear attractive force due to the long range van der Waals forces and sometimes capillary forces, and after a maximum peak (small peak), the tip begins to contact around the interatomic distance, i.e. 1.69 A^o. After contact, the cantilever is elastically deformed, and the interatomic force is repulsive and almost linear until to the plastic deformation region.

Using XYZ piezolelectric actuators with the resolution down to 0.01 nm, very precise positioning is possible. The cantilever deflection Δz can be measured using a laser beam and a photo detector system down to 0.01 nm resolution, or other methods such as piezoresistance or capacitance measurement, etc. Since the stiffness of the probe k_c is known, the normal force on the tip can be computed as $F_s = k_c \Delta z$ assuming at the equilibrium. Controlling the z-motion such that force reaches a reference value in the contact region, the relative motion corresponds to the height at that (x,y) point. Scanning all (x,y) points in a rectangular region, topology data can be held. This method is called *contact imaging*. However, for the manipulation applications, the nano objects to be manipulated are designed not to be fixed on the substrate, and contact-type of scanning can move the objects. Therefore, during imaging, non-contact AFM imaging is required. As the non-contact imaging type, tapping mode imaging is prefereble where soft samples can be scanned with few deformation, and unstabilities due to the water layer on the surface are reduced. In the tapping mode, the cantilever tip is set to several 10s of nm above the substrate, and it is vibrated externally around its resonance frequency f_r by an amplitude equal to its separation distance. Thus, the tip taps to the substrate, and the interatomic forces change the vibration amplitude and frequency. Detecting these changes and controlling the sample/cantilever z-position during scanning, surface topology image is held. Thus, our strategy is *imaging in the tapping mode* and *manipulation in the contact-mode*.

Using AFM also lateral frictional forces can be measured which is very useful for 2-D push and pull object manipulation where friction plays a major role. Frictional force can be measured by detecting the cantilever torsional bending angle using a four-cell photo detector, and knowing the torsional stiffness of the cantilever. In the experiments, the home-made AFM system as can be seen in Figure 4 is utilized [8]. Piezoresistive cantilevers are used where the deflection is measured through a Wheastone bridge. This kind of cantilevers are advantageous for manipulation applications where laser detection systems limit the mechanical design, and motion capabilities of the probe while these cantilevers do not. However, the deflection resolution is almost ten times worse than laser detection one.

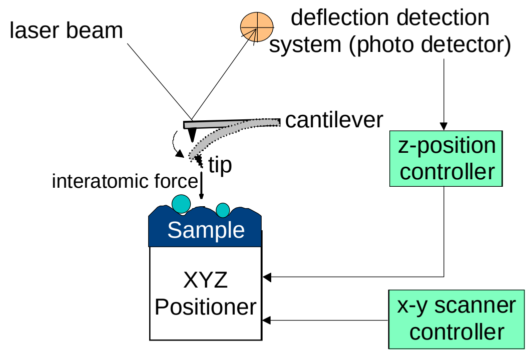

Fig. 2. Structure of a normal and lateral force measuring conventional AFM.

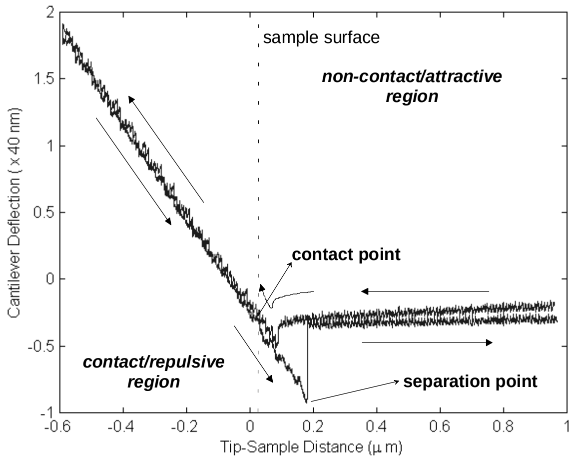

Fig. 3. Interatomic force and distance relation during Si tip and Si surface approach and retraction (experimental).

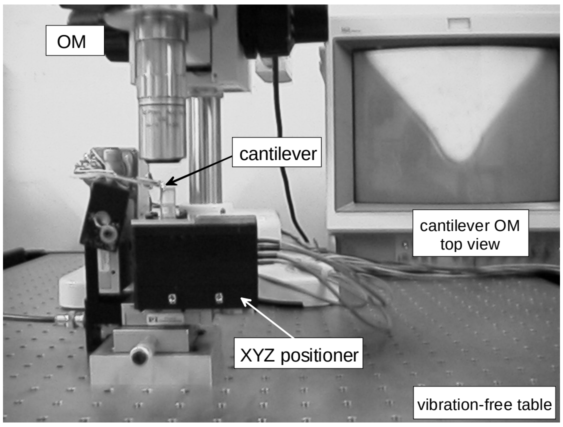

Fig. 4. Photo of the home-made AFM setup with top-view Optical Microscope.

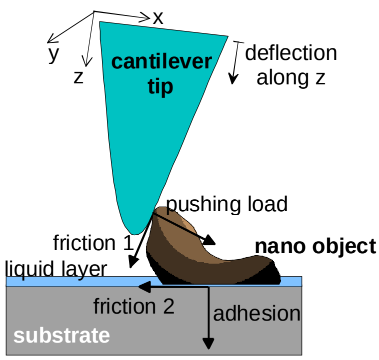

Fig. 5. Interaction forces during pushing nano objects by AFM probe tip.

3.2 Nano Forces

During the manipulation of a nano object using an AFM probe, the interacting forces are shown in Figure 5. All of these forces should be modeled, and the dynamical analysis of the manipulation should be conducted for improving general design rules and strategies. The forces consist of adhesive forces (van der Waals, capillary and electrostatic forces), contact deformation forces, frictional forces, and triboelectrification forces (charge induction on the objects during pushing due to the substrate friction). Modeling of these forces in the spherical particle pushing case is given in [9,10]. From these models, the conditions for a reliable contact pushing of any object are driven as follows:

1. Objects should be precisely movable by contact pushing on the substrate reducing friction between particle and substrate.
    - 1.1. Depositing lubricant monolayer on the substrate, i.e. for a Au object, Silane monolayer on a Si substrate, and Polylysine layer on a Mica [4],
    - 1.2. Minimizing the particle-substrate adhesion (friction is function of external load plus adhesive force at the nano scale [9]):
        - 1.2.1. Selecting proper material types (minimal surface energies),
        - 1.2.2. Reducing the adhesive forces such as capillary force by reducing the humidity level or coating the tip by teflon, or electrostatic force by grounding the tip and substrate, etc.,
    - 1.3. Proper cantilever selection:
        - 1.3.1. high stiffness (10s of N/m) for pushing stability (applying enough load for pushing and breaking the adhesion force during separation from the object after manipulation),
        - 1.3.2. hard tip (Si or Si_3N_4),
    - 1.4. Contact point/angle selection (for applying maximum shearing force such that the horizontal line passing through the object center in spherical particle case),
    - 1.5. High motion accuracy (for precise positioning during pushing):
        - 1.5.1. closed-loop positioners for reducing hystheresis and drift effects,
        - 1.5.2. reducing environmental noise sources (vibration, thermal changes, etc.),
        - 1.5.3. selecting low thermal conductivity materials on the mechanical parts for reducing the thermal drift,
2. Objects should not stick to the tip while retracting the probe after manipulation: (tip-particle adhesion) < (particle-substrate adhesion)
    - 2.1. small tip radius (few 10s of nm) with hard material: small contact area,
    - 2.2. manipulation in liquid (reduces capillary and electrostatic forces),
    - 2.3. tip or particle coating for reducing adhesion forces (latex particles are coated with Au for reducing adhesion due to triboelectrification [9]).

However, some of conditions have trade-offs. Conditions 1.2 and 2 are opposite, then a between optimum particle-substrate adhesion should be designed. Secondly, Condition 1.3.1 results in reduction of force measurement sensitivity such that smaller stiffness means higher force resolution. These trade-offs can be solved depending on the priority in a specific application.

3.3 AFM Position Control

Piezoelectric XYZ actuators are utilized for atomic resolution positioning. These actuators have hystheresis and drift problems depending on the motion duration and range, and temperature changes. For imaging, since xy motion consists of scanning with specified range, actuators can be calibrated off-line using laser interferometry, and these calibration data are then can be used for accurate scanning (in the case of commercial AFMs). However, in manipulation tasks, the tip moves on arbitrary points in a given range; thus, open-loop control is almost not reliable. Therefore, the best is to integrate high resolution sensors such as capacitive, strain gauge, LVDT, or optical sensors to motion axes for closed-loop control. In our system, a Physick Instrumente XYZ closed-loop stage with 10 nm resolution LVDT sensors, 0.1% hystheresis error and 100 μm range in all axes is utilized. The transfer function with stage plant dynamics and PID controller is computed as:

$$\frac{X_s(s)}{X_{sr}(s)} = S(s) = \frac{G_A(K_{sp}s + K_{sI} + K_{sD}s^2)}{s^3 + \left(\frac{\omega_n}{Q} + G_A K_{sD}\right)s^2 + (\omega_n^2 + G_A K_{sp})s + G_A K_{sI}}, \qquad (1)$$

where G_A is the voltage amplifier gain, f_n is the resonance frequency of the stage with $\omega_n = 2\pi f_n$, Q is the quality factor which is related to the damping of the stage, and K_{sP}, K_{sI}, K_{sD} are the PID controller gains. Our fine stage has the values of $f_n = 450\ Hz$ and $Q = 20$ for the z-axis, and $f_n = 200\ Hz$ and $Q = 20$ for the xy-axes.

4 Macro World: Human-Machine Interface

Overall view of the Virtual Reality user interface for tele-nanomanipulation system which consists of force and visual displays can be seen in Figure 6.

4.1 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) [11] 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 (Figure 7). 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 visual feedback, this deficiency can be eliminated by animating the object motions during manipulation using NA/S tool.

Fig. 6. Overall photo of the Virtual Reality user interface.

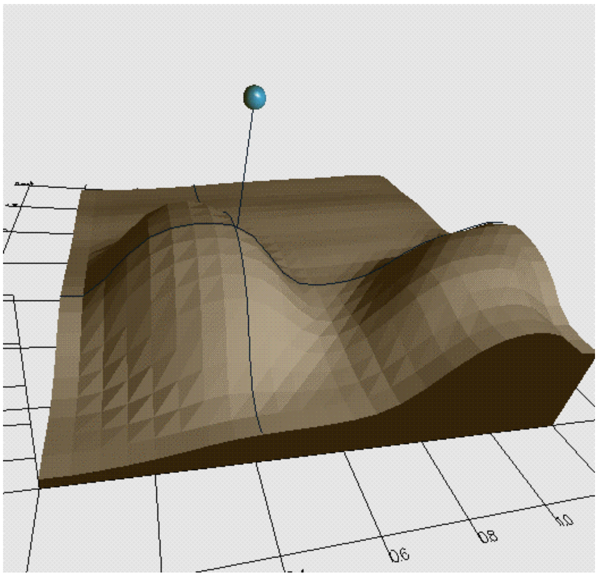

Fig. 7. An example graphics display of Nano Visulator interface for 0.5 µm size latex particles on a Si surface.

4.2 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 [8]. The actual to reference position transfer function can be computed as:

$$\frac{X_m(s)}{X_{mr}(s)} = M(s) = \frac{K_{PA} b_1 (K_{mp} s + K_{mI} + K_{mD} s^2)}{s^4 + b_2 s^3 + (b_3 + K_{PA} b_1 K_{mD}) s^2 + K_{PA} b_1 K_{mP} s + K_{PA} b_1 K_{mI}}, \quad (2)$$

where $b_1=K_t\eta p/(2\pi JL)$, $b_2=R/L$, $b_3=K_eK_t/(JL)$ with K_t is the torque gain, $\eta=0.7$ is the efficiency of the gear box, $p=0.175$ *mm/round*, $J=3.81$ $mNms^2$ is the inertia of the motor, $L=0.55$ *mH* is the inductance, $R=11$ Ω is the resistance, $K_e=0.036$ $V/rads^{-1}$ is the back emf constant, K_{PA} is the power amplifier gain, and K_{mP}, K_{mI}, and K_{mD} are the master PID controller gains.

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 no power transmission from operator to the master arm.

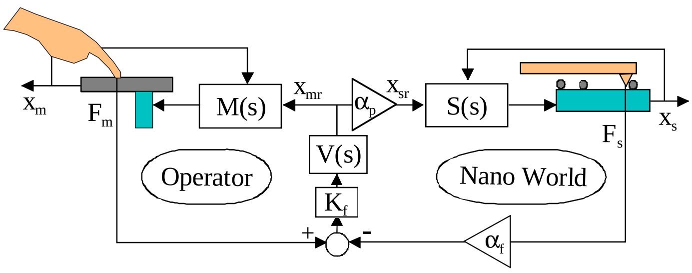

Fig. 8. Bilateral force feedback control system setup.

5 M2N World: Bilateral Teleoperation Control

In the manipulation mode, during approaching and contacting to the surface or the object, or manipulating the object, 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 8 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. $F_s(s)=K\, X_s(s)$, the following equality is held for the forces:

$$\frac{F_m}{F_s} = \frac{K_V}{\alpha_p K K_f} + \alpha_f \ . \tag{3}$$

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.

6 Experiments

Three main experiments have been realized for testing the feasibility of the teleoperation control by touching to a point on a surface [12], 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 Si surface results in the operator and nano force and position as shown in Figure 9. Parameters of the system are $M_v=0.1\ kg$, $B_v=2\ N/(m/sec)$, $K_v=0$, $\alpha_p=8x10^4$, $\alpha_f=25$, $K_f=30$, $K_{mP}=5$, $K_{mI}=0.5$, and $K_{mD}=0.05$. Initial tip-sample position is approximately *100 nm*, and z motion steps are around 10-20 nm. 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.

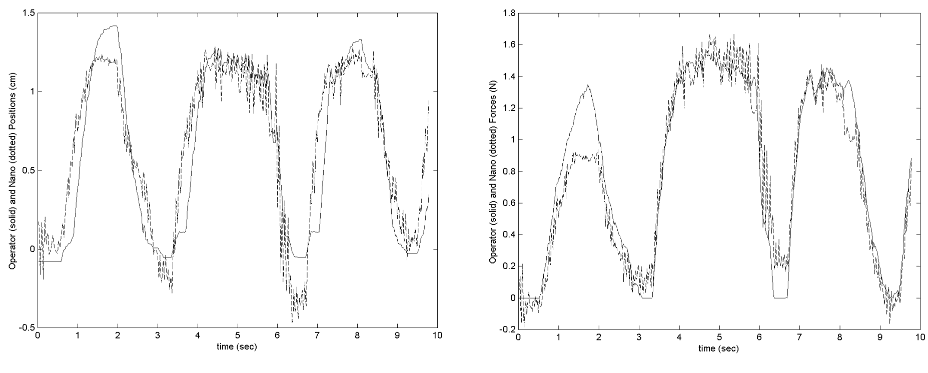

Fig. 9. Touching vertically to a point on a Si substrate: the master (solid) and scaled slave (dotted) positions (left), the master (solid) and scaled slave (dotted) forces (right) vs. time.

Next, a Focused Ion Beam (FIB) fabricated number ‘3’ on Si is felt by the operator by moving in x-y using the mouse cursor. 3-D Nano Visulator view of the surface and scanned points on the sample are shown in Figure 10a and 10b respectively. Depending on the surface height frequency, and x-y motion speed the frequency of felt height increases as in the Figure 10c. If the motion speed is decreased each feature can be felt more precisely. In this experiment, for only feeling the topology information, only position ideal response is held, and force response is not realized.

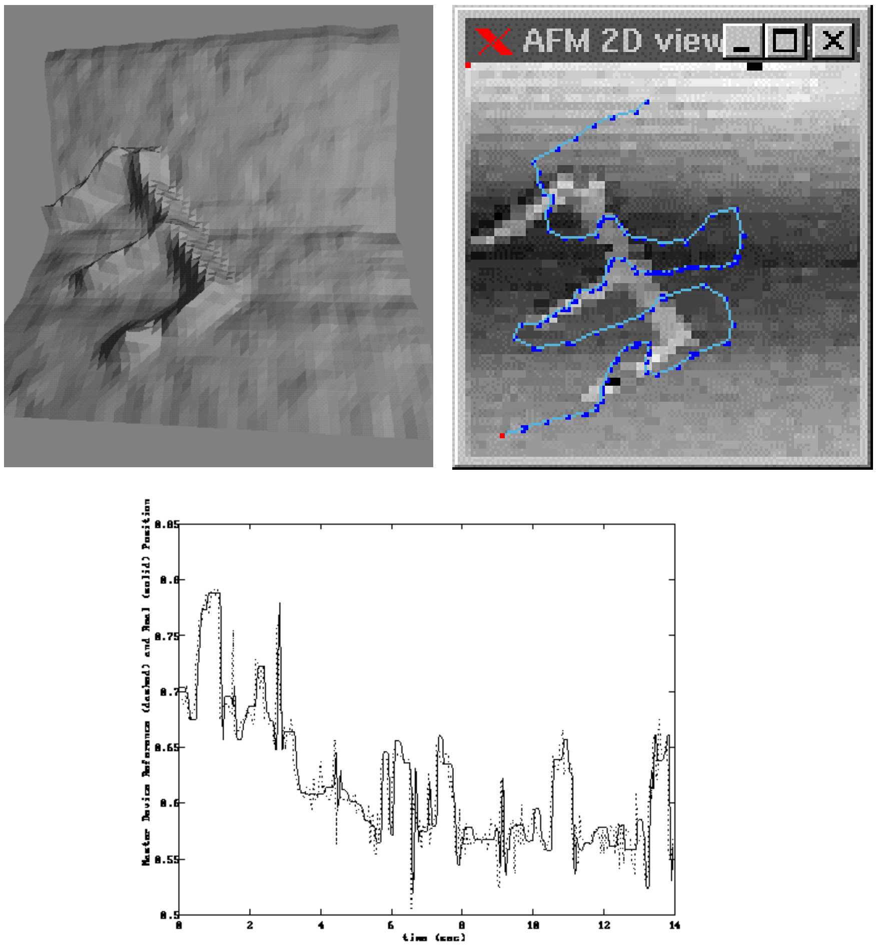

Fig. 10. (a) (left upper image) FIB fabricated character ‘3’ is shown in 3-D graphics (8 μm x 8 μm x 0.1 μm size image), **(b)** (right upper image) Top-view 2-D image is used for x-y scanning on the surface for feeling the topology feedback, **(c)** The topology feedback on the operator hand vs. time: actual position (solid line) and measured reference scaled surface height (dotted line).

Finally, *2.02 μm* gold coated latex particles are positioned on a Si substrate by pushing on 2-D in ambient conditions with *60%* humidity level. In Figure 11, a particle is added to a line of other particles successfully. Coating with gold reduced the triboelectrification forces. Cantilever parameters are $k_c=20\ N/m$ and *25 nm* tip radius. Optical Microscope images are utilized for real-time monitoring with *95 nm/pixel* resolution. Modeling of forces and their evaluation with the experimental results are given in [9].

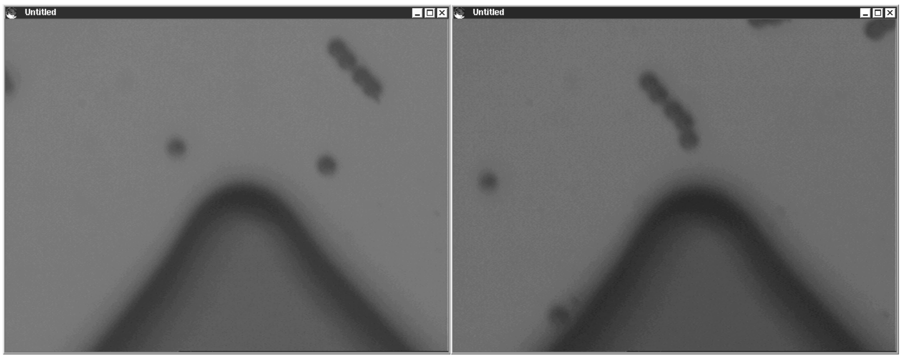

Fig. 11. 2-D positioning of a gold-coated latex particle to a line of other particles by contact pushing where the initial configuration (left) and last one (right) are shown.

7 Conclusion

In this paper, a teleoperated nano manipulation system using home-made AFM as the nano manipulator and sensor is introduced. Regarding to nano physics, requirements for these kind of systems are reported. Besides of 3-D visual feedback in the user interface, a 1DOF haptic device has been constructed for nano scale force sensing and generating motion commands for the AFM. Introducing teleoperation control system with Virtual Impedance approach, nano scale forces or topologies are felt by the operator. Preliminary experiments on teleoperation system and object manipulation show that the system can be utilized for tele-nanomanipulation experiments.

As the future work, the sizes of the manipulated objects will be decreased to few 10s of nanometer, and types of manipulated objects will be increased. Nano carbon tubes which are very important for nanotechnology applications will be pushed and their tribological, adhesive, mechanical, electrical and magnetic properties will be analyzed. Furthermore, biological object manipulation and mechanism understanding experiments will be conducted. On the other hand, by increasing the number of AFM probes it is possible to pick and place nano objects which can be utilized for constructing 3-D nano structures and devices.

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