A Haptic Interface for Human-in-the-Loop Manipulation at the Nanoscale

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Abstract

This paper outlines major challenges that we are facing in interfacing a human user with objects in the nanoworld via a haptic interface. After a review of prior efforts at haptically-enabled nanomanipulation systems, we present the current state of our nanomanipulator system. We then discuss current research issues including the direct-Z mode, force modeling, data transfer rates and the stability of the haptic interface. Results of nanomanipulation of single-walled carbon nanotubes are presented. It is our hope that the insight gained by the human user of a haptic interface to SPM will lead to scanning algorithms that can automatically adjust the SPM parameters based on the properties of the nanosample and the substrate under investigation.

1. Introduction

The scanning probe microscope (SPM) is an extremely versatile instrument that has steadily evolved from its invention in the early eighties [1-2]. SPMs are now routinely available in many research labs throughout the world and are widely acknowledged for ushering in the study of matter at the nanoscale. The underlying principles of an SPM are quite simple but yet completely different in many significant ways from more traditional microscopes [3]. Essentially, the SPM works by measuring touch, using a sharp tip (often called a proximal probe) positioned about 0.2 to 1 nanometer above a substrate. The highly local information provided by the microscope is achieved by a combination of the sharpness of the tip as well as the small separation between the tip and substrate. Fig. 1 illustrates a diagram of a typical interaction paradigm. A key discovery during the development of SPMs was the realization that with a sufficiently sharp tip (essentially atomically 'sharp'), a quantitative three-dimensional image of surfaces can be obtained, often with atomic resolution.

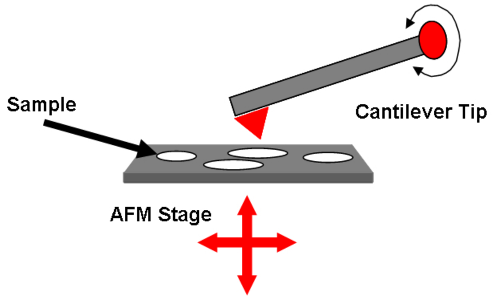

Figure 1. Diagram of cantilever-stage interaction.

The ability for SPMs to manipulate as well as image at nanoscale dimensions has enabled a wide variety of novel experiments during the past fifteen years. The collective outcome of this work is largely responsible for the current world-wide interest and enthusiasm in nanotechnology. A common conclusion often reached by many SPM users is that better control of the SPM tip would open up an innovative type of possible experiments at the nanoscale. A number of attempts to realize this goal have been reported. The standard paradigm is an SPM combined with a haptic interface to allow better control of the scanning probe tip.

While this prior interest in SPM/haptic interfaces has resulted in a number of publications, the full realization of a versatile nanomanipulator is still somewhat of a scientific curiosity. The development of a generally useful tool for widespread nanoscale manufacturing has still not been demonstrated. Part of the difficulty is the perception that a nanomanipulator provides a serial interface to manipulation that is far too slow for useful production purposes. While this is certainly true for current implementations of a nanomanipulator, it is likely that the experience gained by studying the *process* of nanomanipulation will lead to new insights that in turn will result in expert scanning algorithms capable of adjusting scanning conditions to optimize the study of a substrate of interest. Such developments have occurred in computer numerical control (CNC) machining in which cutting, drilling and feed speeds are now automatically set based on the materials of construction and part dimensions. A parallel development in SPM will surely occur in which SPM scanning parameters will be automatically based on the outcome of a few well-defined fiducial diagnostics performed in advance to determine the nanoscale adhesive and elastic properties of a sample under study. A versatile nanomanipulator offers much within this context and can contribute extensively to a database of parameters judged relevant by skilled human operators.

With this motivation in mind, we have designed a new generation nanomanipultor which is built around the 3rdTech NanoManipulator (NM) software. In what follows, we describe the progress we have achieved to date in implementing this advanced nanomanipulator system, and discuss the major research issues to be addressed in the future.

2. Prior Efforts

A number of research efforts have centered on the idea of developing a nanomanipulation system that couples a haptic device with a nanoscale imaging device. Examples of such systems and their corresponding research are found in [4-19]. In this section, we will briefly discuss the results and contributions from these efforts, and highlight how we feel we can improve upon their successes and failures.

In 1990, Hollis *et al.* coupled the "Magic Wrist" to a STM (scanning tunnel microscope) at the IBM Thomas J. Watson Research Center (Yorktown Heights, NY) [4]. Using the "Magic Wrist", a 6-DOF (degrees of freedom) force and torque-feedback haptic interface based on magnetic levitation principles, they were able to move the interface in the *xy* plane and feel the wrist motion in *z* as the STM tip moved over the surface being examined. Using this system, they were able to explore and feel sputtered gold films and cleaved graphite while viewing images using standard STM techniques. One problem with their system was the reported mechanical and electrical noises that felt like "moving one's hand over a rough vibrating surface." This noise limited the position and force resolutions achievable by their system.

During the same time frame as the "Magic Wrist" was being developed, Hatamura and Morishita produced their Nanorobot System. In [6], they describe a bilateral joystick mechanism coupled with a scanning electron microscope. This research aimed to determine a bidirectional data mapping between the human operator and the nanoscale world by mapping a 10cm translation in the workspace to a 10μm motion of a robot's end effector. Their apparatus consisted of two joystick controls that allowed the user to control both a 3-axis robot and a 6-axis actuating table. In using this approach, they were successful in their attempt to make small scratches in aluminum substrates. They reported that operators could manipulate a 10μm sample with a 0.1μm resolution while using their haptic interface and viewing the sample via a stereo image. However, their system was limited in that forces were transmitted to the user through a joystick confined to a plane.

Roughly a decade later, Sitti *et al.* demonstrated the design and functionality of their Tele-Nanorobotic system using a 1-DOF haptic interface [7-14]. Their system visualized 3-D images of the samples using OpenGL software functions [8]. They were likely the first group to have modeled nanoscale force interactions within the context of haptic feedback [10-12], to address the scaling issue between forces and displacements in the macro and nano worlds, and to consider the effect of limited bandwidth and hardware disturbances [7]. In [9] they proposed a set of requirements for manipulating objects at nanoscale. They identified force and length *scaling* between the nano/micro world and the macro environment, along with the *stability* of the associated bilateral teleoperation, as the two essential issues that have to be resolved in order to produce a viable nanomanipulation system. In [13] and [14] focus was placed on control strategies for nanomanipulation systems such as direct teleoperation and semi-autonomous control.

Taylor *et al.* demonstrated how a force feedback robotic arm could be interfaced to an STM and allow a human operator to feel nanometer scale data while seeing it though a head mounted display [20]. Termed the Nanomanipulator (nM), this system interfaced a head mounted display, a force feedback Argonne-III Remote Manipulator and an STM. The goal of this research was to grant the ability to interact with atomic surfaces in real time while providing 3D visual feedback and data analysis capabilities. They were able to allow users to feel data stored on a computer disk using Microscape, a prototype viewing system.

Later modifications of this system led to the results in [15], and the commercial distribution of the software by 3rdTech Inc. (Chapel Hill, NC). To date, researchers have used the technology to focus on the research of biological and material science samples. Examples included manipulation of the Tobacco Mosaic and Adeno viruses, and DNA and carbon nanotubes [15].

The UNC/3rdTech NM system utilizes a unique algorithm for generating feedback forces. Using a local planar approximation technique originally developed for computer graphics, the system reconstructs the surface geometry of the sample being imaged from the limited data returned by the SFM (scanning force microscope). A feedback force is subsequently generated based on the calculation of the penetration depth of the haptic tip into this virtual surface [21]. By first fitting the SFM data to a local surface, the NM system effectively filters out the high-frequency noise in the SFM tip position and thereby assuring a convincing feel of surface features. Furthermore, the feedback force calculated from the reconstructed surface profile changes smoothly, and the stability of the haptic interface can be maintained for extended periods of time.

Another commercially-available nanomanipulator system has been developed recently by NanoFeel in Switzerland [personal communication, Francois Conti, 2004]. The NanoFeel300 allows a user to control the cantilever tip in a Nano-R AFM (Pacific Nanotechnology, Santa Clara, CA) with a Delta 6-DOF force-feedback device (ForceDimension, Switzerland), and to receive real-time force feedback based on cantilever deflection. The force-feedback loop runs at 4 kHz, and the AFM's tip position is closed-loop controlled (with preset limits to prevent the tip from crashing into, say, a CNT). NanoFeel is currently developing models that will allow real-time update of visual rendering when a CNT is being modified.

Other recent research efforts include [5] where Marliere *et al.* present the results with their nanomanipulation system. Using a custom 1-DOF haptic device (the Force Feedback Gestural Device), they were able to interface with an AFM while granting users multisensory feedback. Force feedback was enabled through their haptic device, while sound was delivered through a loud speaker. Their system was also equipped with a virtual modeling component that allowed them to simulate nanoscale interactions using an experimentally validated model of their AFM. During these virtual interactions, a linearized model of the Lennard-Jones potential was used to calculate atomic reaction forces that were relayed to the user via the haptic device.

Guangyong Li *et al.* reported some of their recent developments in this research area in [16-19]. The authors describe their attempt to develop an augmented reality nanomanipulation system by modeling the cantilever-tip interaction. Their system combines a commercial AFM, CCD camera, optical microscope, PHANToM, CPU and two computer monitors. In [16], the system was used to complete tasks such as nanolithography, as well as pushing and cutting of nano particles. The authors also discussed how to compensate for false force signals and crosstalk using a compensation algorithm during manipulation [19].

3. The Purdue Nanomanipulator System

Figure 2 shows a system-level diagram of the key components of the Purdue Nanomanipulator System. Its central component is the software of the commercially-available NM system (DP-100, 3rdTech Inc., Chapel Hill, NC), an interactive visualization and control system for SPM. Our system expands the capability of the DP-100 system in two ways. Firstly, instead of an Explorer SPM (Veeco Instruments, NY) that the original system was designed to interface with, we use an SPM developed by Nanotec Electronica^{TM} that features WSxM, an open architecture application program allowing for flexible and sophisticated control of the SPM.[1] As shown in Fig. 2, the Nanotec SPM is run by a dedicated DSP system controlled by WSxM. Secondly, we have developed drivers that allow other haptic devices to be interfaced with the NM. The original DP-100 system was shipped with a 3-DOF PHANToM device (desktop model, SensAble Technologies, Woburn, MA). We have since added a 6-DOF Delta device that provides torque in addition to force feedback. As shown by the dashed box in Fig. 2, both the WSxM and the haptic interface communicate with the NM via the Virtual Reality Peripheral Network (VRPN), a network-transparent protocol for handling peripheral devices in a virtual reality system [22]. Our future plans include designing a controller that will stabilize the haptic interface during sudden force changes. This controller will be integrated into the NM software of the final system and will enable new features. For example, in the original DP-100 system,

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[1] The DP-200 system from 3rdTech Inc. allows the NM to be interfaced with the Nanotec SPM.

the PHANToM receives a triangulated surface model from the NM, and renders forces locally by monitoring the penetration depth of the stylus into the virtual surface. In our future system, the controller will send force commands directly to the haptic device.

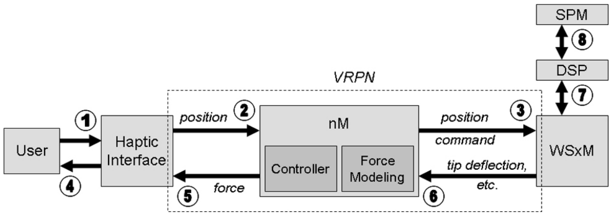

Figure 2. System diagram of Purdue nanomanipulator system.

4. Research Issues

To put our work in the context of previous efforts, we will extend Hollis *et al.*'s work by allowing a human operator to directly control the tip-sample separation (which had been attempted, but not successfully, before), and expand Sitti *et al.*'s work from 1-DOF to 3 or 6-DOF. The ultimate goal is to faithfully recreate the physics occurring at the nanoscale for the human operator, so that the user can gain intuition about nanoscale interactions and be able to manipulate nanostructures more efficiently. Our interdisciplinary team combines expertise in haptics, SPM scanning, control, dynamic systems modeling, and software engineering. In what follows, we discuss the main issues that we will address in our work.

4.1. The Direct-Z Mode

The term "direct-Z" was probably first coined by the inventors of the UNC/3rdTech NM system [15]. It refers to a user's ability to directly control the z-direction (up-down) motion of the SPM scanning tip and to receive force feedback in real time. One benefit of operating an SPM in the direct-Z mode is to tap on a sample and estimate relevant properties such as adhesion and stiffness. By allowing a human user to *feel* the surface stiffness, it might for instance be possible to quickly identify local regions of contamination distributed across an otherwise clean but rough substrate.

As far as we are aware, existing nanomanipulator systems allow the user to control the xy, but not the z, position of the SPM tip.[2] Researchers at UNC and 3rdTech Inc. had attempted the direct-Z operation using their NM, but found the instability of the haptic device to be a major challenge. This may not be surprising considering the sometimes abrupt changes in the force between the cantilever tip and the sample (see Sec. 4.2). When the stage carrying the nanoscale sample is moved in the xy (horizontal) plane, the z position of the SPM tip is mainly affected by the surface topography of the sample. When the tip is moved towards or away from the sample in the z (vertical) direction, however, the SPM tip can go through unstable stages, such as "snap to contact" (see also Sec. 4.2). Since the force changes estimated from tip deflection are now sent directly to the haptic interface (instead of going through the effectively low-pass filtering stage of fitting data onto a smooth surface), the Direct-Z mode imposes a greater challenge on the stability of the haptic interface. Therefore, an advanced controller is required to ensure the stability of the haptic device (see discussion in Sec. 4.4)

4.2. Force Modeling

This section discusses the functionalities to be implemented inside the "Force Modeling" block shown in Fig. 2. As mentioned in Sec. 2, force feedback in the original DP-100 NM system was calculated to be proportional to the penetration depth of the PHANToM stylus tip inside a surface model constructed from SPM tip-deflection data [21]. As a result, the UNC/3rdTech NM system renders the surface *topography* of the sample, but not the interaction *force* between the SPM tip and the sample. Our goal is to faithfully model the actual force between the SPM tip and the sample based on cantilever deflection data, and apply appropriate scaling to the derived force value to make it perceptible to the human operator.

In order to model and appropriately render the force interactions, we must have access to the current system states. The inherent flexibility of WSxM enables this access since it is capable of relaying up to 17 channels of data (link 7 in Fig. 2). The channels include: the x, y, and z positions of the stage, the in-phase and out of phase components of oscillation amplitude, four channels of user defined inputs, the output of the system's phase lock loop, surface topography, as well as normal and lateral forces. Our current system restricts the NM's data access to the topography, normal and lateral force channels (link 6 in Fig. 2) since increasing the amount of data that is transmitted across the network also increases computational delays. These parameters are sufficient to characterize the microcantilever deflection and twist as it is rastered in a vibrationless fashion across a substrate.

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[2] We have recently learned that the NanoFeel system allows direct-Z operation, but does not deal with tip or haptic interface instability.

A typical experiment might require local information about substrate stiffness. If the scanning is stopped and the tip is positioned over a feature on the substrate, information about the local tip/substrate interaction can be obtained by executing a force-distance experiment in which the vertical deflection of the cantilever is monitored as a function of tip-substrate separation. Such data provides considerable information about interaction forces and potentials at the nanoscale. In Fig. 3, positive cantilever deflection corresponds to a loading of the tip against the substrate while a negative deflection indicates a downward motion of the cantilever from its equilibrium position which is defined to be zero at large tip-substrate separations.

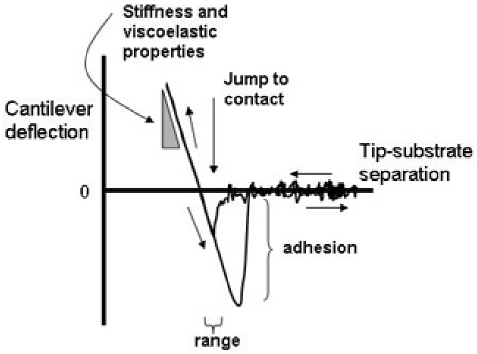

Figure 3. Schematic diagram of a force vs. distance experiment illustrating the physical properties related to important features.

The important features of interest in Fig. 3 include i) a small downward bending of the cantilever when the tip/substrate interaction becomes non-negligible (useful in determining the range of the tip-substrate interaction); ii) an abrupt jump to contact that occurs when the gradient of the interaction force matches the spring constant of the cantilever; iii) a loading/unloading region that contains information about the stiffness and viscoelastic deformation of the substrate; and iv) a lift-off force which provides information about the adhesive force between the tip and the substrate. The salient features of this plot can be haptically rendered only when the response times and noise immunity of the haptic system are well understood. Any information that can be haptically transmitted to the SPM user in a rapid and faithful fashion would be particularly useful in the characterization of the physical properties of unknown nanoscale objects. To begin with, we will focus on the sensing of stiffness and viscosity properties of the nanosample by the user of the haptic interface (the slope marked by the gray triangle in Fig. 3).

4.3. Data Transfer Rates

Data transfer rate is a key specification of the performance of any nanomanipulation system. We determine the minimum update rates needed at the eight communication links in Fig. 2 from the point of view of acceptable functionality, and compare them with the corresponding currently achievable rates (Table 1). It is well established that human motor output is bandwidth limited to 2-3 Hz [23], yet we can perceive vibrations up to 500 Hz, with the highest sensitivity for vibrations at around 200-300 Hz [24]. To adequately capture the movement of a user, the update rates at links 1–3 need to be 10-20 times the bandwidth of human movement [25]. As shown in Table 1, the currently achievable rates at links 1–3 are adequate.

Table 1. Desired and currently achievable update rates, in Hz, for our nanomanipulator system. See Fig. 2 for location of corresponding communication links.

Link #	Desired	Current	Limited by
1	20–60	1,000	standard haptic update rate
2	20–60	1,000	standard haptic update rate
3	20–60	20–70	graphics processing time
4	≥ 3000	1,000	standard haptic update rate
5	≥ 3000	1,000	standard haptic update rate
6	≥ 3000	≈ 10	Link 7
7	–	≈ 10	Windows Operating System
8	–	15,000	–

To take full advantage of the human somatosensory perception, however, the update rates at links 4–6 need to be at least 3 kHz [26]. Currently, we use a standard update rate for haptic loop at 1 kHz (links 4 and 5) which is barely adequate. Depending on the nature of the virtual haptic objects being rendered, we have argued for higher update rates (e.g., in the case of rendering a relatively stiff textured surface [26]). Although this rate can be achieved within the VRPN framework, the bottleneck is the rate at which WSxM can return information from the SPM (link 6). Currently, the parameters from the SPM are being transmitted at about 10 Hz when the haptic interface is introduced in the feedback loop. The low update at link

6 is caused in turn by a low update rate between the DSP and the WSxM (link 7). This is largely due to the Windows operating system, which is not designed to support a real time application. If we assume that WSxM can return 100 samples at a rate of 10 Hz, then we will receive 1000 samples per second, *except* that the samples will be delayed by as much as 100 msec. The variable delay associated with the sampled data from the SPM can seriously affect the system stability. We are currently working towards increasing the update rates at links 6 and 7 to about 20 Hz, although this is still far from the desired update rate at these links. Finally, the real-time DSP system interacts with the SPM at a rate of 15 kHz.

4.4. Controller Design Consideration and Implementation

Given the nonlinear force interactions between the AFM tip and the sample as well as the interactions between the human operator and the haptic interface, careful consideration is needed to prevent instability when the two systems are coupled together. As a result, a well designed controller is needed to maintain high fidelity transfer of information at the appropriate range of operation and maintain overall system stability (Fig. 4). Many controller design approaches can and have been used to address these issues in similar applications, e.g. telerobotics. However, with a human operator in the loop, it is desirable that the controlled system is passive; i.e. it does not act unless it is acted upon by the human operator. Passive systems are described as systems that can not generate energy and that remain passive when combined with similar systems. One of the advantages of passivity-based control approach is that the design objective of making the coupled/combined system (human/machine and/or machine/environment) passive inherently imply certain stability conditions (e.g., passivity is a sufficient condition for system stability). Therefore, for the Direct-Z operation, we focused on developing a passivity-based, coordinated motion and force controller to maintain system stability and to provide high fidelity haptic rendering.

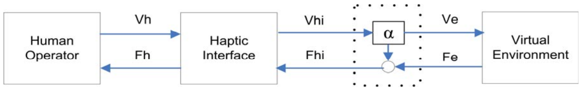

Figure 4: Basic Structure from the Hannaford PO/PC.

Within passivity control, there are many design approaches with different focus and merit. Hannaford *et al.* introduced a passivity observer (PO) and passivity controller (PC) combination for haptic interfaces [27]. During times when the system becomes active, as determined by the passivity observer, necessary energy is released via a passivity controller to drive the system to a stable state. This method allows passivity control to be applied to a broad range of haptic systems without extensive knowledge of the system parameters. A modified version of the passivity-based control algorithm proposed by Hannaford *et al.* [28] was developed and integrated with the Purdue Nanomanipulator System (see Figure 4). Preliminary experiments showed encouraging results as well as issues that need further investigation.

For our experiment, the Delta Haptic Device was used as the input device and for force feedback. The task involved the operator trying to maintain contact with a vertical virtual wall with a stiffness of 7 N/mm at an update rate of 1 kHz. Figure 5 shows a pictorial view of the experimental setup. Basically, the operator tried to maintain the contact between a contact-point (oval) and a flat virtual surface (blue rectangle) located in the *yz* plane**.** The stiffness value, 7 N/mm, was chosen experimentally by searching for a value that would result in an unstable surface if it was slightly increased. Figure 6 shows the response of the system without using the controller. Notice that the resulting virtual environment (VE) force is relatively smooth and continuous. Accordingly, the user is able to sense the wall, and the force sensation is stable. Note the relatively small changes in the *x* position, which results in a small and quantized velocity value. The *y* positions are consistent with the different parts of the work space. Furthermore, the actual system energy tracks the reference energy, although at a slightly lower value. If the controller was enabled, it would activate shortly before four seconds into the experiment when the actual energy falls below that of the reference energy, in an effort to have them track each other.

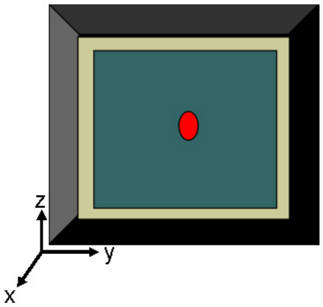

Figure 5: Illustration of the experimental setup.

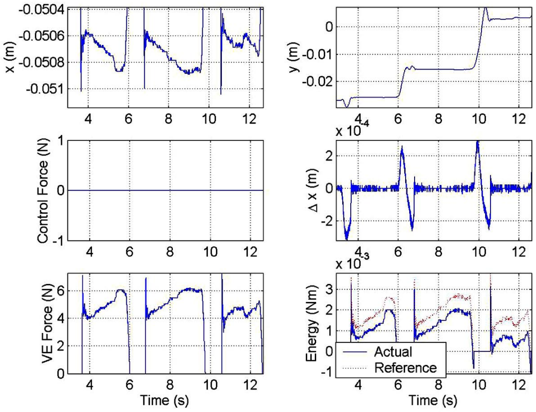

Figure 6: Results without controller.

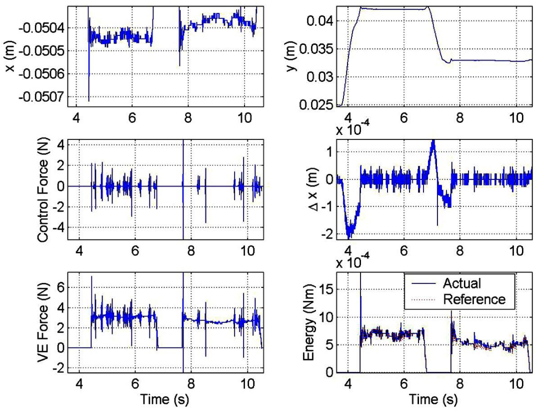

Figure 7: Results with controller enabled

In the previous example, the system exhibits acceptable behavior. One would expect similar, if not better performance, when the controller is engaged. To test this assumption, we ran the identical experiment with the proposed controller. Figure 7 shows the results. Notice that the controller engages soon after 4 seconds into the experiment when it detects that the actual energy falls below the reference energy. As in the previous experiment, the x position motion is very small. However, in this case, the resulting virtual environment force is not smooth and somewhat erratic. Although the actual energy tries to track the reference energy, as specified by the algorithm, the user experiences an unstable force output. Furthermore, we were not able to stabilize the system for any stiffness values in excess of 7N/mm.

After analyzing the data, we were able to attribute the instabilities to the quantization of the position input. This effect is amplified during periods where the sensor readings report consecutive identical position measurements, resulting in a zero velocity value. During these times, a control action is not sent to the device, even if the stored energy falls below the reference energy. This check is necessary to ensure that the control signal is bounded (since it is inversely proportional to velocity). As a result, it is possible for the system to become active, i.e. generate energy, without the controller acting to dissipate it. Similar experiments were run at higher haptic update rates (up to 2.5 kHz) and similar results were obtained.

Based on these results, we are currently working on modifying the PO/PC algorithm to overcome the quantization effect of the position measurements. A major limitation is that the resolution of the optical encoders cannot be easily increased. A well-known technique used to address the impact of the loss of resolution during low velocity periods of optical encoder measurements involves counting the period of each encoder pulses rather than counting encoder pulses per unit time. However, since we do not have access to the encoder interface circuit, another approach is needed. We will augment the quantized position measurement and the associated velocity estimation with carefully designed position and velocity estimators. This is, again, a well documented approach. The potential draw back is that the additional phase lag associated with the estimation will impact the achievable bandwidth of the device. High resolution position and velocity measurements and high bandwidth control loop are needed to improve the current Purdue Nanomanipulator System.

5. Current Capabilities of Our System

We have used the Purdue Nanomanipulator System to manipulate carbon nanotubes (CNTs) which is a sheet of carbon atoms rolled up into a tube-like structure. There has been a tremendous amount of research involving CNTs since their discovery in the early 90's. In spite of this effort, it is still very difficult to quickly characterize the electrical and mechanical properties of these tube-like cylindrical nano-structures. Our research is ultimately focused on the use of CNTs in nanoelectronic devices such as CNTFETs. Our goal is to characterize the electrical properties of CNT junctions and to measure the effect of mechanical deformations on single walled carbon nanotubes (SWCNTs) [29]. We have focused on the manipulation of individual SWCNTs (~ 1 to ~1.5 nm in diameter) and ropes of SWCNTs.

Silicon cantilevers having resonant frequencies in the 140-300 KHz range have been selected. Scanning probe imaging was performed in non-contact mode while all manipulation was performed in contact mode.[3] The maximum scan size was 30μm×30μm, while a typical scan size of 1μm×1μm was most often used. Typically a scanning speed of 1 Hz was used; the average time to acquire an image with a 256×256 resolution was ~ 4 minutes.

For our current system, when the haptic interface is engaged, the user can control the (*x, y*) position of the AFM tip with a haptic device. The current version of the UNC/3rdTech NM software allows several modes of operation of the scanning tip during a modification: sweep mode, straight line mode and freehand mode. During a modification, WSxM records and transmits the raw (*x, y*) coordinates of the scanning tip, topography, normal force and lateral force – all of which can be readily retrieved from the NM software. The NM software also displays a 3-D visual rendering of the topography data.

By controlling the forces acting between the AFM scanning tip and the sample, we were able to translate, bend, straighten and cut CNTs. Figure 8 shows a typical sequence of images that demonstrate these capabilities. The task was to bend a straight rope of SWCNTs (~450 nm in length) into a circular shape. In Fig. 8e, we observe that a sharp bend in the nanotube causes buckling at a localized location and a discernible kink is produced. Upon further manipulation, the nanotube can be bent into a more circular configuration (Fig. 8f). Since there appears to be no permanent kink in the SWCNT, we conclude that there is no permanent deformation in the nanotube.

Such experiments shed light on the bending stiffness of the nanotubes, their adhesion to the underlying substrate, and the friction between the nanotube and the substrate. Prior theoretical studies [30] have shown that the adhesive forces can deform nanotubes, thereby affecting their electron transport properties. Any curved equilibrium of the nanotube on the surface is thus a balance between the adhesive forces and the elastic restoring forces. The greater the nanotube curvature achievable in these experiments the greater is the adhesion force. Similarly, the rolling and sliding friction of nanotubes on a surface are also of importance for the controlled assembly of nanotubes for nanoelectronics and sensor applications [31, 32]. The nanomanipulation experiments described above also allow the direct measurement of these friction forces.

6. Conclusion

We have described our work on a haptic interface for manipulation and measurements at the nanoscale, and outlined main research issues yet to be addressed. Such a system will enhance a user's ability to gain intuition about the properties and interactions of nanoscale objects. Until very recently, SPMs have been primarily used to obtain visual 3D images of surfaces. We are now enabling an operator to feel the interaction of the tip and a nanoscale object through a haptic interface. These efforts, if successful, will pave the way for robots that can assemble devices and make efficient and reliable measurements at the nanoscale.

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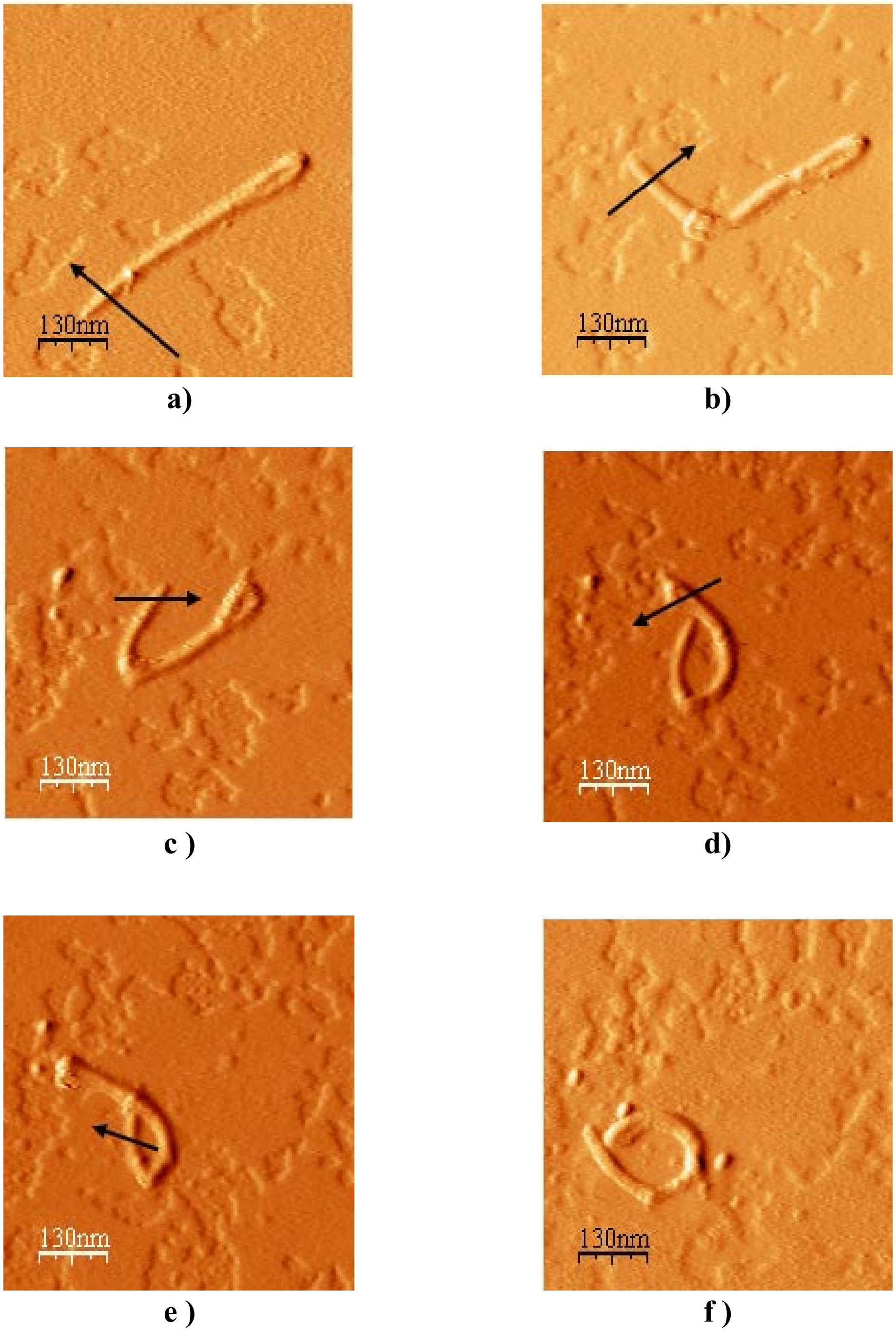

a) **b)**

c) **d)**

e) **f)**

Figure 8: Manipulation sequence of 450nm long rope of SWCNTs on mica. (a-d) A straight rope of nanotubes is manipulated and bent by an AFM tip along a path represented by the arrows. (e) Buckling occurs due to sharp bending. (f) There is no permanent deformation in the structure of the nanotube(s).