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A Programmable AFM-Based Nanomanipulation Method Using Vibration-Mode Operation

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Abstract — **A novel method is developed to effectively manipulating nano-entities to predefined positions and orientations autonomously. In this method, the nanomanipulation process is programmed by planning and executing the AFM tip's movement, and the amplitude of probe-tip's vibration is measured in real-time to detect the boundary of the nano-entities under manipulation – which will change as a function of the distance between the probe-tip and a nano-entity due to their inter-molecular force interactions. After the start-position and destination are defined by the user interface software, the nanomanipulation process is operated automatically. The result from each manipulation step is detected and used as the information for feedback control on the subsequent operating step. Using this method, CNTs can be manipulated to any position and orientation. Experimental results show that this manipulation method is effective and more efficient (reduce operation time by >50%) than nanomanipulation processes with a human operator in the feedback loop.**

Keywords — ***AFM-Based nanomanipulation, Automated nanomanipulation, Nanomanipulation, Nano-robotics, Tapping mode.***

I. INTRODUCTION

Nanodevices such as nanosensors and signal electric transistors will potentially have many advanced applications in the coming decades. However, universally accepted methods to efficiently and reliably fabricate nanodevices are still non-existent. Thus, the techniques of nanofabrication and nanoassembly, which are the design and manufacturing of devices with dimensions measured in nanometers, have been of broad interest for the past decade and is considered as a 'must-have' high technology for the 21st Century. As an essential technique for prototyping nanodevices, nanomanipulation using atomic force microscope (AFM) has been developed for more than a decade already. This manipulation method can be used to manipulate various samples, such as conductive/nonconductive materials and bio-samples, and can be executed in atmospheric condition, even in liquid. The AFM's high position precision and relatively easy operation procedures guarantee its broad usage in various research fields. The typical nanomanipulator using an AFM includes a Virtual Reality (VR) interface between an AFM and a haptic joystick [1]. Many kinds of VR-interfaced AFM systems have been introduced and various applications, including particle pushing [2] and CNT/ cell manipulations [3], were realized.

Most VR-interfaced nanomanipulators today require an operator in the control loop to plan the path and compensate the spatial uncertainties, such as thermal drift of the PZT actuator. Thus, this reduces the efficiency. Moreover, the system cannot repeat the same manipulations exactly. To conquer the drawback mentioned above, automated nanomanipulation is a desirable choice for nanofabrication using an AFM. Some pioneering work has been performed by several groups on this subject. Requicha's group developed a practical automatic system for 2-D assembly tasks at the nanoscale. The planner covers a whole range of problems in planning the assembly of nanoparticle patterns, including object assignment, obstacle detection and avoidance, path finding, and path sequencing [4]. Xi's group developed a CAD-guided automatic nanomanipulation system [5]. Using their system, the manipulation paths for both nanoparticles and nanorods are generated automatically based on the CAD model of a nanostructure. Ammi and Ferreira have also developed a path planning method using Virtual Force Reflection [6] [7].

Moreover, the typical nanomanipulation systems lack real-time feedback information from the nano-world to verify the nanomanipulation result in real time. The nanomanipulation system must get a new image after every step of manipulation, so the efficiency is extremely low. To deal with this problem, an augmented reality system was developed by Xi's group [1]. The operator could manipulate continuously with force and visual feedback. However, the real-time feedback displayed on manipulation interface is not the real manipulation result, but the computed result from the dynamic model of the manipulation procedure. Due to the complexity of the nano-environment, an exact model of the manipulation procedure is impossible to obtain, which influences the authenticity of the shown "visual" feedback result.

In addition, the AFM tip can only exert manipulating force on a point on the nano-entities. Thus, it is a good method to manipulate 0-D and 1-D nano-materials that are rigid such as nano particles and nanorods. However, 1-D nano-materials such as CNTs and DNAs are flexible, and hence could not be easily manipulated by an AFM tip, so the development of an effective and efficient nanomanipulation method for 1-D soft

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nanomaterials is also required. Developing multi-tip AFM systems offer possible solution, but introduce many difficult problems, such as the control strategy and the coupling motion of these tips.

Here we present a technique call **p**rogrammable **n**anomanipulation **u**sing **v**ibration-mode **o**peration (P-NUVO) which uses feedback information from the molecular interaction force between the probe-tip and a nano-entity under manipulation. Experimental results show that this method is effective and efficient to manipulate flexible (or soft) nano-entities and overcome the three main problems addressed above to some extent. Essentially, the P-NUVO method uses the probe-cantilever's vibration amplitude signal as feedback information to verify the manipulation results, and consequently, if the AFM tip's path is well-planned ahead, the system can do the nanomanipulation automatically. The remaining of this paper is organized as follow: section II introduces the concept of nanomanipulation based on the vibration-mode AFM with real-time feedback information. The method of P-NUVO is expanded in the section III. The system architecture and experiment results will be presented in section IV. Finally, the conclusion is presented in section V.

II. VIBRATION-MODE AFM NANOMANIPULATION WITH REAL-TIME FEEDBACK

Most of the AFM based nanomanipulation systems use the contact-mode operation. In this case, the feedback is turned off to adjust the relative distance between the AFM tip and samples by the operator when a manipulation is executing. Due to the softness of the contact-mode AFM cantilever, the tip must push down to the sample surface, and thus this will often destroy the surface of the sample. On the other hand, vibration-mode based nanomanipulation has also been developed for the past few years, but it drew little attention in AFM-based nanomanipulation field. There are two existing methods of vibration-mode based nanomanipulation. One keeps the control loop engaged, while the other turns it off. The first method was reported in [8] and [9]. A detailed analysis of the principle of the second nanomanipulation method was presented in [10]. The second method has the benefit that the control system can adjust the AFM tip's position in Z direction if the sample surface is tilted. In our work, we use the second method, but with real-time feedback information.

When using the vibration-mode AFM to manipulate nano-entities, the control loop in the Z-direction could be accessed during the nanomanipulation process. That is, the AFM tip could be controlled to exert enough pushing force in vibration-mode by adjusting the amplitude of the tip's vibration, which in term could be performed by monitoring the OMSPV (Opto-electronic Measurement Signal of Probe Vibration) of the AFM system. This idea was demonstrated by our group in [11]. For example, MWCNTs could be manipulated on a mica substrate using vibration-mode AFM, as shown in Fig. 1. In the experiment shown, the amplitude of OMSPV was set to 1V for scanning the image, while to 10mV during manipulation. As the scanned image indicates, the vibration-mode manipulation force could be large enough to break the MWCNT if the attractive force between the MWCNT and mica substrate is much greater than the pushing force required to break the MWCNT.

We have found that the AFM probe's vibration can offer real-time feedback information on whether a manipulation process succeeds or not. The amplitude of the OMSPV will be in an unstable state of probe vibration when the tip contacts with the edge of CNTs due to the real-time adjustment of the AFM control system as shown in Fig. 2. A detailed interpretation of this feedback information was offered in [11].

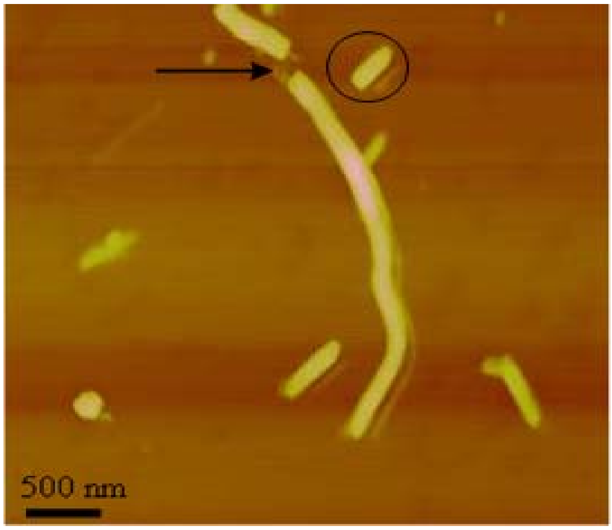

Fig. 1. Pushing CNTs on mica surface using vibration-mode AFM. The arrowheads denote the direction of the tip's push.

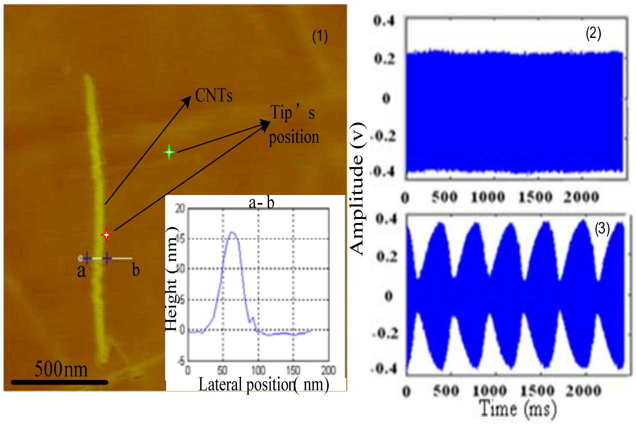

Fig. 2. Experimental results of position detection of CNTs. The substrate is polymer (PMMA), and the scanned range is 1.3 µm. (2) and (3) show the amplitude of OMSPV vs. time without (i.e., the green cross position) and with (i.e., the red cross position) CNTs, respectively.

III. THE P-NUVO METHOD

A sketch of the possible manipulation steps using the P-NUVO method is provided in Fig. 3. The solid lines denote a 1-D flexible nano-material, and the broken arrowhead lines denote the path and direction of the pushing tip. The left end of the broken arrowhead lines is the start line of AFM tip's movement, and the arrowhead position is the destination of each push. According to the distance between the start-line and the destination, the manipulation procedure is divided into N parts. The lengths of preceding N-1 (or less than that) parts are equal. Each step's length of the last part (or the last several parts) is adjusted according to the predefined nano-entities orientation. The manipulation result can be verified using the amplitude of OMSPV as feedback information. If the manipulation succeeds, the AFM tip will contact the edge of the object, and the amplitude of OMSPV will be unstable, similarly to the signal shown in Fig. 2(3). If a manipulation fails, a new push is executed until the manipulation succeeds. This means that no "nanoimaging" (scanning) is required during the manipulation procedure to verify the manipulation result. A flexible 1-D nanomaterial can be manipulated to any orientation by adjusting the angle α . A flowchart of this novel method is shown in Fig. 4.

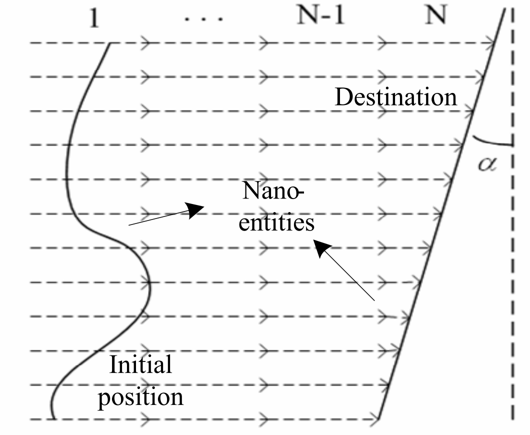

Fig. 3. A sketch of an example of P-NUVO method manipulation strategy.

IV. EXPERIMENT RESULTS

Based on the principle presented above, contrast experiments between the P-NUVO method and the NanoMan II function of the Veeco Inc.'s commercial program were performed by our team. In NanoMan II functions, the AFM tip's position is controlled by the mouse through an interface between the operator and an AFM image. The P-NUVO method is implemented through an application program interface (API) between the operator and the AFM. According to the task, the path of AFM tip is programmed using VC++ development environment to create a dynamic link library (DLL) file. And then, the DLL file is loaded in the AFM control system through the API. We have created a user-interface software (UIS) already, through which all the process could be done automatically. The only thing an operator needs to do is to define the start position and destination of the manipulation task. After that, the AFM system can execute the entire manipulation automatically. Fig. 5 shows the experimental results of manipulation a flexible CNT. The image 0 of Fig. 5 is the initial state of the CNTs. The images from 1 to 10 are the manipulation results using NanoMan II, and the image from 10 to 11 is the manipulation result using P-NUVO. The scanning range is 4.5 µm. It took about 35min using the NANOMAN II to push the CNTs to the left end of the region (a 2^{nd} operator used ~17min to perform the same task). Moreover, it is quite difficult to manipulate the CNTs into a straight-line configuration. And, due to no real-time feedback from the nano-world, a "Refresh Region" is required after one step of manipulation. On contrast, the novel method described in this paper needs only ~7min (2 experiments were performed) to manipulate the CNTs from the left to the right into a much straighter configuration.

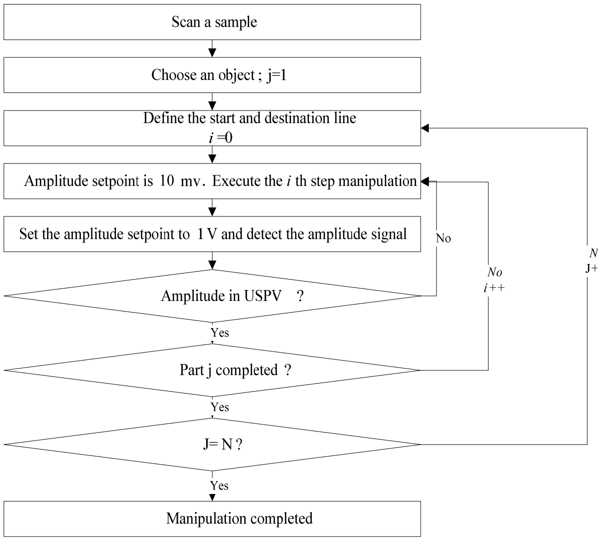

Fig. 4. The process flowchart of P-NUVO.

Another contrast experiment aimed to validate whether the P-NUVO has advantages in the manipulation of nanoparticles was also performed. Fig. 6 shows the manipulation results using NanoMan II functions. The diameter of gold nanoparticles is 50 nm and the scanning range is 2.4 µm. The aim is to manipulate the nanoparticles from the central part of the region to the left and right edges of the scanning region. Because of spherical shape of nanoparticles, we were able to execute several steps to manipulate different nanoparticles to the destination before updating the AFM image. This is a bit different from the condition of manipulating CNTs, i.e., the CNTs are too flexible, so that the "nanoimaging" needs to be updated periodically during a manipulation process. Because of the lateral resolution of AFM, the nanoparticle marked by "b" in image 3 of Fig. 6 is in a "big particle" composed by three nanoparticles marked by "b", "c" and "d" in image 2. It is cost about 5 minutes to finish the manipulation. On contrast, Fig. 7 presents the results of using the P-NUVO method. The AFM tip's path plan is a bit different from that of the pushing CNTs. Because of the nanoparticles' spherical shape, the path of each push is programmed to directly reach the final destination. To avoid the lost of nanoparticles, the distance of each push is set to 5 nm. If this is set to 10 nm, the manipulation may fail and some nanoparticles are not pushed to the destination (the experiment result is not shown here). Using our novel method, it only cost ~1/3 time of the manipulation using NanoMan II to accomplish the same task, i.e., ~110 second. These experimental results conclusively show that the novel P-NUVO method has some unique advantages compared with the traditional method.

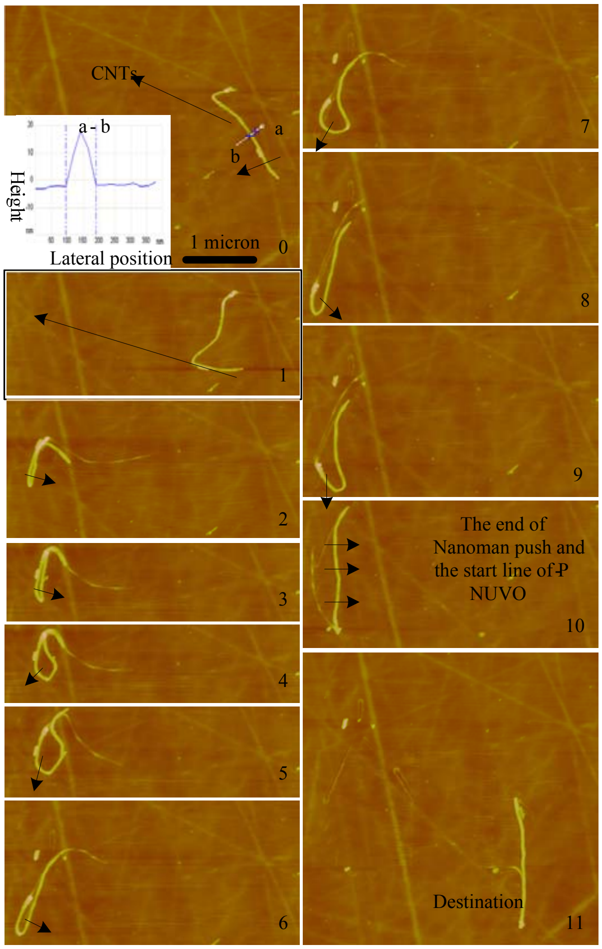

Fig. 5. The contrast experiment results. The arrowheads denote the direction of the tip's push. Image 0 is the initial position of the CNTs. Images from 1 to 10 are the results from pushing using Nanoman II, and from Images 10 to 11, the CNTs are manipulated by the novel P-NUVO.

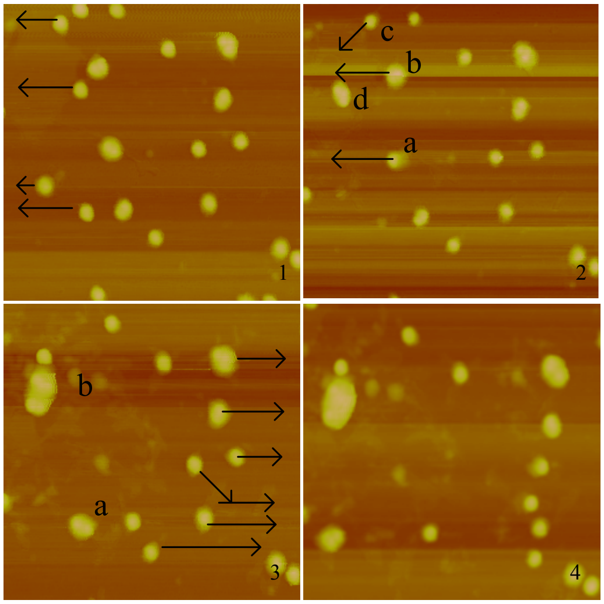

Fig. 6. Manual manipulation of gold nano-particles using NanoMan II made by the Veeco Inc.. It is likely that during the manipulation process, particles could be joined together. For example, Particle b, c, and d in image 2 were joined to form particle b in image 3. The particle "a" in image 2 was not pushed to the destination, but other place, as shown in image 3.The manipulation process here took ~5min to complete.

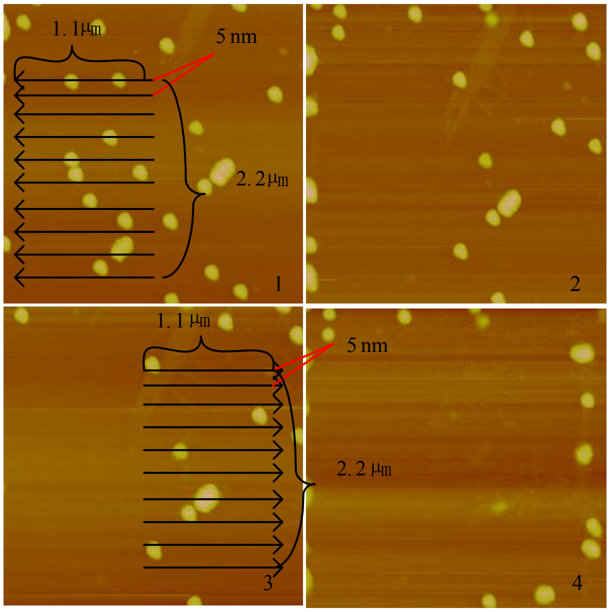

Fig. 7. Automatic manipulation of gold nano-particles. Image 1 and 3 show the initial position of particles and the pushing strategy. Image 2 and 4 show the manipulation results. The scanning region of 1 and 3 is 2.4 micron and that of 2 and 4 is 2.6 micron. It costs about 110 seconds for each manipulation.

V. CONCLUSION

A novel P-NUVO method is presented in this paper. Using this method, the drawbacks of nanomanipulation using contact-mode method has been addressed to some extent. After a path planning of the manipulation strategy, a manipulation can be entirely executed automatically. Moreover, this novel method also offers real-time feedback information to verify the result of every manipulation step. This information not only can be used as a feedback for the control system, but also can be used for real-time visual feedback for an interface-software, which is our future work. We have shown that this new method improves the efficiency of the AFM-based nanomanipulation. A well-planned AFM tip's path makes it easer to manipulate 1-D nanomaterials, such as CNTs. The experimental results show that the efficiency and effectiveness can be improved dramatically (>50%) over human-in-loop nanomanipulation techniques.

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