Vibration-Mode Based Real-Time Nanoimaging and Nanomanipulation

Zhihua Liu[1, 3], Yongliang Yang[1, 3], Yanli Qu[1], Zaili Dong[1], Wen J. Li[1,2,*], and Yuechao Wang[1]

[1] Robotics Laboratory, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China
[2] Centre for Micro and Nano Systems, The Chinese University of Hong Kong, Hong Kong, China
[3] Graduate University of the Chinese Academy of Sciences, Beijing, China

Abstract — **A novel method based on vibration-mode of the atomic force microscope (AFM) for nanoimaging and nanomanipulation is introduced in this paper. With this approach, the amplitude of OMSPV (opto-electronic measurement signal of probe vibration) can be used as a feedback signal to detect and control the operation state under vibration-mode. By controlling the amplitude of AFM probe, the tip-sample interaction force can be sufficiently adjusted. Therefore, vibration-mode of AFM system can be used to manipulate nano-entities just as in using the standard contact-mode manipulation strategy. Using the novel method, nanoimaging and nanomanipulation could both be performed in vibration-mode, and the damages of the sample and probe tip can be reduced significantly. Furthermore, by detecting the amplitude of OMSPV change during operation, the precise position information between the probe tip and nano-entities (e.g., CNTs) can be determined automatically as well. Experiments show that the amplitude of OMSPV will be in USPV (unstable state of probe vibration) when the tip is at the edge of CNTs due to the real-time adjustment of parameters of the AFM control system. Such USPV can be used to determine whether the manipulation succeeds in real-time. The correlative analysis and signal processing method is also presented in the paper.**

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

I. Introduction

Nanofabrication, which is the design and manufacturing of devices with dimensions measured in nanometers, has been of widespread interest for the past ten years and is seen as a promising high-tech for the 21st Century. As a possible method for nanofabrication, AFM-based nanomanipulation has been under development for at least a decade and is now accepted as a technique for prototyping nanodevices as well as other applications. The typical nanomanipulator using an AFM includes a Virtual Reality (VR) interface between an AFM and a haptic joystick [1]. A great variety of VR interfaced AFM systems have been introduced where realized applications include particle pushing [2] and cell manipulation [3]. However, the main problem of this kind of nanomanipulator is that it needs an operator in the control loop to plan the path and compensate the spatial uncertainties. Thus the typical manual nanomanipulation method can not be used for mass production due to its labor-intensiveness and unreliable repeatability. Hence, automatic manipulation is a desirable choice for nanofabrication using an AFM. Several groups have already performed some pioneering work on this subject. Makaliwe and Requicha developed a practical planning system for 2D 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]. Ning Xi's group developed a CAD-guided automatic nanoassembly 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 developed a path planning method using Virtual Force Reflection [6] [7]. However, in all of the above work, their solutions are all based on the contact mode of AFM. Since the feedback signals are only the normal and lateral PSD (position sensitive device) signals in contact mode, they are insufficient for the automatic nanomanipulation. Moreover, the tip may exert a relatively large normal force on the sample. Subsequently, fragile samples are damaged (as shown in Fig. 1), and the tip tends to wear out rapidly.

On the other hand, how to automatically detect the success of nano-operation by controlling the AFM probe still is difficult. We should also mention here that Requicha's group has also done some work to compensate the thermal drift --the major cause of the spatial uncertainty [8] [9]. They used Kalman filtering technique to estimate the thermal drift, but it could only estimate the drift in a short period of time, and no discussion is provided by them on the problem of integrating the estimated drift into automated path planning. In this paper, a novel manipulation method using AFM in vibration-mode is demonstrated. Experiments show this new method to be a simple and efficient way to get more feedback information during a nano-operation process. Essentially, based on the measurement of probe amplitude, the nanomanipulation can be programmable and the operating uncertainties will be reduced when using an AFM.

II. Amplitude Signal Detection and Processing

A. Position Detection of CNTs

In this section, the nano-entity (e.g., a CNT) position detection method using amplitude of OMSPV is presented. During AFM operations, when the tip stops scanning, it maintains vibration at the "amplitude setpoint" on the sample. "Amplitude setpoint" is a value at which the tip's vibrating

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Contact author: **wen@mae.cuhk.edu.hk; Wen J. Li is a professor at The Chinese University of Hong Kong and also an affiliated professor at The Shenyang Institute of Automation, CAS.*

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RMS amplitude must maintain. We have found that this amplitude of OMSPV is significantly different when the tip is at a CNT's edge versus the tip is "far away" from the same CNT. Fig. 2 (a) is an AFM scanning result of a CNT on a polymer (PMMA) substrate. When the tip is on the substrate, far away from the CNT (the green star denotes the AFM tip's position), the amplitude of OMSPV is very stable, as shown in Fig. 2 (c). However, when the tip reaches the edge of the CNT (the red star), the amplitude of OMSPV will be in USPV, as shown in Fig. 2 (d). A large number of experiments performed by our team show that the USPV signal obtained relative to the position of the tip and CNTs is repeatable. Hence, using this signal as feedback, a strategy to automatically find the actual position of the CNTs can be implemented.

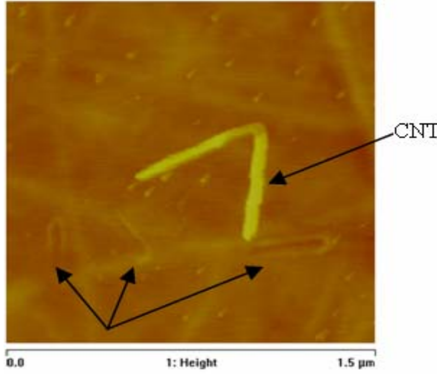

Fig. 1. The damaged sample surface after manipulation in contact mode operation. The three arrowheads point out the damaged surface.

B. *Theoretical Analysis and Signal Processing*

This section provides the theoretical analysis and signal processing method for the observed USPV amplitude collected by OMSPV. Due to the vibration of the probe, the tip will randomly "knock" on the nano-entity or substrate when the tip is at the edge of the nano-entity, which can be considered as a disturbing input to the probe control loop. Since the frequency of probe vibration in tapping mode is always more than 200 *k*Hz, when a disturbing pulse is less than the stabilizing time of the probe control loop, the system can not keep a stable state and will be in USPV mode. This is why the amplitude of OMSPV changes as shown in Fig. 2.

The sketch of an AFM cantilever-probe with dimensional parameters is shown in fig. 3. The cantilever's vibration can be theoretically described by the spring-mass-damper system model. Here, the model employed is described in Fig. 4, where the tip is modeled as a sphere of radius *R* and mass *m*; the cantilever is modeled as a spring with elastic coefficient *k*. Z is the distance between the cantilever and the sample at equilibrium position when only gravity is acting on it. The displacement of cantilever from the equilibrium position is given by *x*.

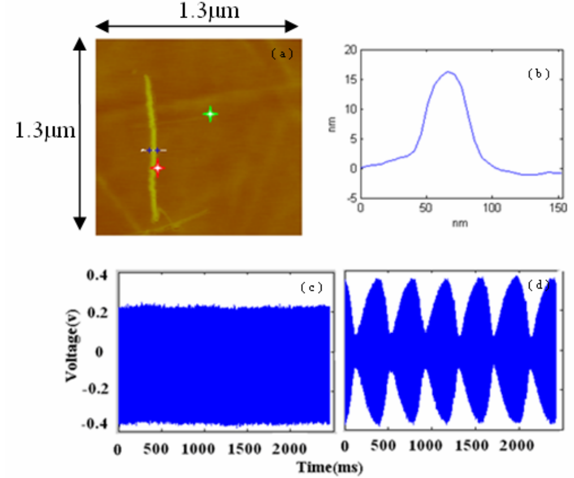

Fig. 2. Experimental results of position detection of a CNT. The scanning range is 1.3 µm, the substrate is polymer (PMMA) and the height of the CNT is less than 20 nm as shown in (b). The small stars in (a) represent the position of the tip. (c) and (d) are the oscilloscope plots showing the amplitude signal of the probe. When the tip is at the green star position, the amplitude signal is shown in (c). When the tip is at the red star position, the amplitude signal is shown in (d).

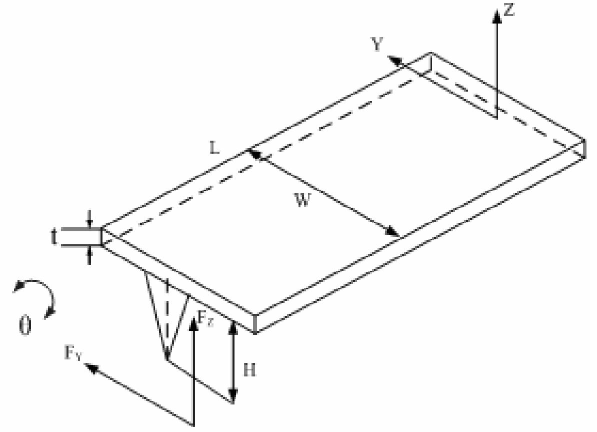

Fig. 3. The sketch of an AFM probe with dimensional parameters, W, L, and t, which are the width, length and thickness of the cantilever, respectively; H is the height of the tip.

The dynamical differential equation of the spring-mass system is given as:

$$mx'' + \frac{m\omega_o}{Q}x' + kx = F_{ts} + F_0 Cos(\omega t) \quad (1)$$

In the above equation, *m* and *k* are the mass and elastic coefficient of the AFM cantilever, respectively; ω_0 is the angular frequency of the tip's vibration; x is the displacement

of the tip while vibrating; Q is the quality factor; F_{ts} is the force between the tip and the sample, and $F_0 \cos(\omega t)$ is the drive force acting on the cantilever.

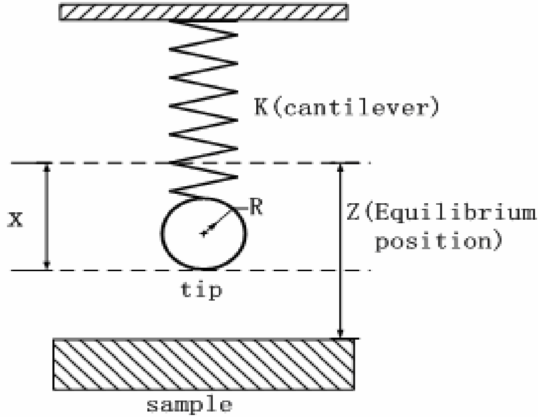

Fig. 4. Sketch of the spring-mass-damper system model of an AFM probe.

Equation (1) is used to analyze the cantilever's vibration characteristics. The probe used in the manipulation experiments is made by Veeco Instruments Inc., and the model is MPP-11100- Tap300. The simulation analysis parameters are provided by the manufacturer, as shown in the Table 1.

Table . 1 The major parameters of the simulation.

t (*μm*)	*L* (*μm*)	*W* (*μm*)	*H* (*μm*)	*E* (*GPa*)	*m* (*Kg*)	*k* (*N/m*)
4	125	35	15	130	1.13e-9	40

The quality factor can be obtained experimentally and it is commonly about 400, which is the valued used in our simulation analysis. As a dynamical system, the vibration probe's stability time is $8Q/\omega_0$. The disturbing signal is a pulse signal, with amplitude of 5 nm and period of less than $8Q/\omega_0$. Fig. 5 is the Matlab simulation result of the vibrating probe used in our experiments. It is consistent with experimental data which means the theoretical analysis mentioned above explains the experimental results well.

In order to make use of this amplitude of OMSPV as feedback information, it must be processed properly. There are several methods to deal this problem, such as RMS (Root Mean Square, as shown in equation (2)) or a low pass filter. The RMS method and the low pass filter can both be used to obtain the amplitude variations of the OMSPV. In our current work, the RMS method is employed in the experiments. The raw data is gathered through an AD data acquisition card, with the sample rate of 8 *kHz*. The RMS is computed for every 80 data, and then the variance of the amplitude of OMSPV is calculated. Thus, the difference between different amplitudes of OMSPV could be detected. A sample experimental result is shown in Fig. 6, which was collected during the manipulation of a CNT. Figure 6 (a) and (b) are the raw data of amplitude signals, and (c) and (d) are the processed data. Using this method, the variations of amplitude signals can be detected in real-time.

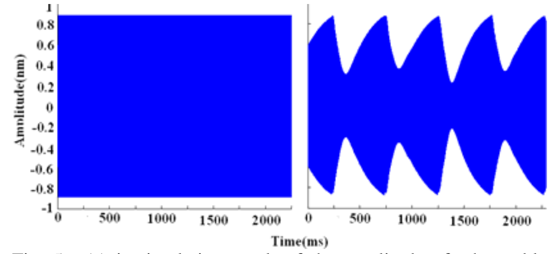

Fig. 5. (a) is simulation result of the amplitude of the stable probe vibration, and (b) is the simulation result of the disturbed probe vibration.

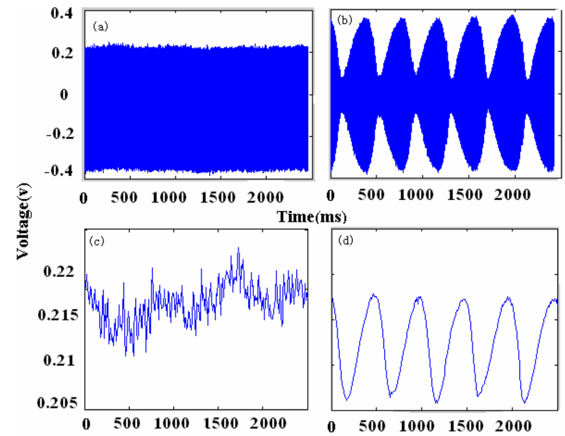

Fig. 6. Amplitude data from RMS data processing. (a) and (b) are the raw PSD amplitude data; (c) and (d) are the processed amplitude results.

$$RMS = \frac{\sqrt{x_1^2 + x_2^2 + x_3^2 + \ldots + x_n^2}}{n} \quad (2)$$

III. MANIPULATION METHOD

This section presents the nanomanipulation approach based on vibration-mode signal detection. Experiments show that this novel method can be use to manipulate CNTs as efficient (or better) as the standard approach of using contact mode of AFM for nanomanipulation. Furthermore, amplitude of OMSPV can be used to obtain in real-time the nano-entities' position. So, this approach will eventually provide real-time feedback information to an operator. Meanwhile, the feedback information can also indicate if a "push" manipulation has succeeded. Ning Xi's group has developed an augmented reality system to show manipulation results almost in real-time [1]. Their system takes advantage of the dynamic model of the manipulation procedure to update the manipulation result.

However, using the feedback signal mentioned in this paper, we can get the actual condition of whether a manipulation is successful or not without any dynamic model.

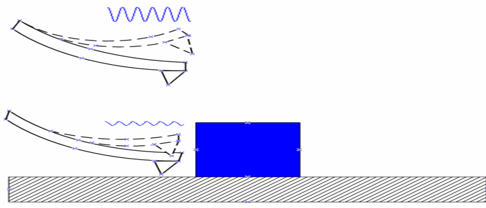

Fig. 7. Vibration-mode based nanomanipulation. The amplitude of probe vibration is adjusted as a function of where the probe is relative to a nano-entity.

The AFM tapping mode is commonly believed to be an imaging method for nanoscale material. Few researchers use this vibration-mode to manipulate nano-entities. However, through modulating the amplitude of probe's vibration, the stiffness of the probe can be changed properly. Thus, this vibration-mode has some characteristics of the AFM contact mode. Because the stiffness of AFM probe in tapping mode is quite large, the tip can offer a useful force to actualize a manipulation when the vibration amplitude is small enough. The benefit of this method is as follows. 1) the tip does not contact the substrate with a large force, because it is in vibration mode. Thus, this method will protect the tip and the substrate very effectively. 2) The stiffness of the AFM probe in tapping mode is quite large, so it can offer a larger push force than using contact mode AFM probe. Fig. 7 represents the principle of nanomanipulation using an AFM in vibration-mode. Zhiguo Liu reported a similar method in [10] as well.

In our experiments, the amplitude of OMSPV was made to be about 0.01 V in manipulation and about 1 V in scanning. Fig. 8 gives the procedure of such manipulation process. After the tip arrived the destination point, the amplitude of OMSPV will come back to about 1 V and the tip will stay there for several milliseconds to verify whether the manipulation is successful. If the manipulation succeeds, the USPV will be detected; else, the operation is presumed to have failed. Since the frequency of the tip vibration is about 200 *k*Hz, 10 *ms* is enough for USPV detection. We have performed many experiments to verify that this manipulation procedure is efficient.

Fig. 9 is a CNT manipulation result using this procedure. The scanning range is 1.3 µm. The Fig. 9 (a) is a scanned picture of CNTs before manipulation. After using the manipulation procedure mentioned above, the CNT is pushed 10 times to make it straight, as shown in Fig. 9 (b). The total manipulating time is less than half minute. Obviously, this is a very efficient way of nanomanipulation compared with the typical nanomanipulation method using contact mode. And, as mentioned earlier, with further development, this novel method could provide a way for automatic nanomanipulation.

IV. CONCLUSION

In this paper, we present a novel nanomanipulation method using the *vibration-mode* of the probe tip of an AFM. Through real-time USPV detection, the method can offer real-time feedback information to an operator to verify the result of a manipulation. Another advantage of this method is that it can protect the nano-entities and AFM tip very effectively. We are currently enhancing this novel method of nanomanipulation procedure to demonstrate a fully automated nanomanipulation system in the short future.

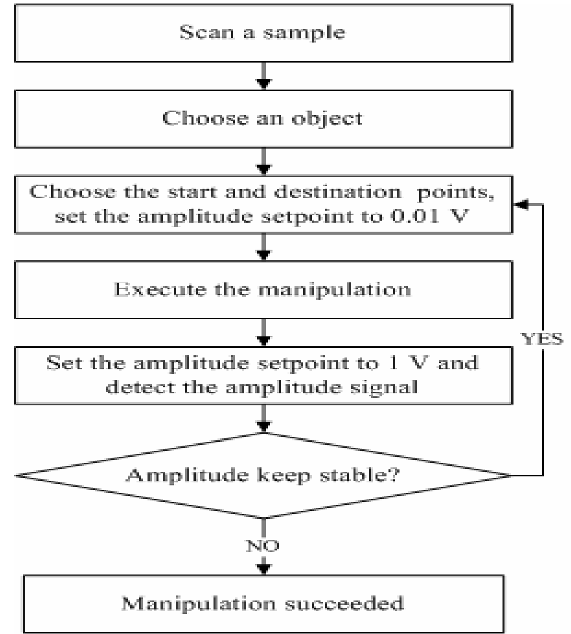

Fig. 8. Flow chart of manipulation procedure in vibration-mode operation of an AFM.

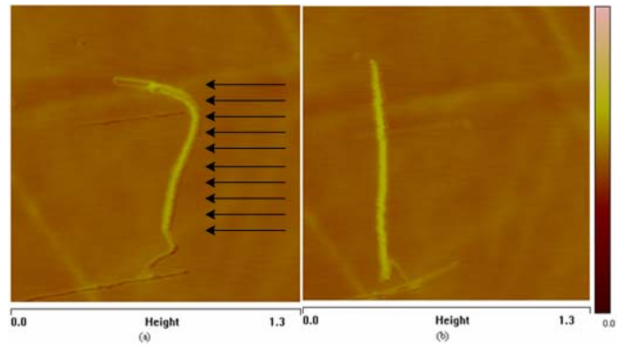

Fig. 9. Experimental results using the manipulation procedure discussed in this paper. The scanning range is 1.3 µm. (a) is the CNT before manipulation; (b) is the CNT after manipulation. The arrowheads represent the manipulation direction.

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