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FORCE AND VISUAL INFORMATION ACQUISITION IN AFM BASED ROBOTIC MWCNT MANIPULATION

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Real-time force and visual information during MWCNT manipulation is required for online controlling MWCNT assembly based on atomic force microscope (AFM). Here real-time three-dimensional (3D) interactive forces between probe and sample are obtained according to PSD signals based on the proposed force model, and MWCNT manipulation process can be online displayed on the visual interface according to probe's position and applied force based on the proposed MWCNT motion model. With real-time force and visual information acquisition and feedback, the operator can control online MWCNT's manipulation process by adjusting the probe's 3D motion and applied forces. MWCNT push and assembly experiments verify the effectiveness of the method, which will be used in assembling MWCNT based nano device.

Keywords: MWCNT manipulation; nano force information; visual information; Atomic Force Microscope (AFM).

1. Introduction

Atomic Force Microscope [Binnig *et al.*, 1986] (AFM) has been proven to be a useful tool to manipulate materials and structure in the nanometer scale, and several manipulation methods have been proposed [Schaefer *et al.*, 1995; Junno *et al.*, 1995; Hansen *et al.*, 1998; Requicha *et al.*, 1998]. However, these manipulation methods can be cataloged into scan-design-manipulation-scan mode, and their main problem is the lack of real-time information feedback, which means that the operator cannot see, feel and eventually control the manipulation process, and the manipulation result can only be verified by another new scan for each manipulation step. Obviously, this manipulation mode is inefficient and inflexible, and the probe is also easier to be worn or broken without force feedback and control.

For solving the problems, various nanomanipulation methods with the assistance of different haptic device have been introduced, such as one degree of freedom (DOF) force feedback device [Sitti and Hashimoto, 2000, 2003] 2-DOF force-feedback game joystick [Rubio-Sierra *et al.*, 2003], 3-DOF haptic device [Guthold *et al.*, 2000; Kim *et al.*, 2002] and even 6-DOF magnetic levitation device [Hollis *et al.*, 1990]. Among them, some researchers not only used a haptic device to facilitate nanomanipulation with force feeling, but also tried to display the manipulation process by constructing a static three-dimensional (3D) visual interface [Sitti and Hashimoto, 2000, 2003; Guthold *et al.*, 2000]. However, on one hand, practically it is difficult to get the nano forces due to many unmeasurable parameters in their force calculation equations. On the other hand, nanoparticle's motion process or nano-environment change cannot be seen in the static visual interface even with an optical microscope due to the limitation of optics wavelength.

Very recently, some researchers have tried to real-timely display the surface contact deformation by using fuzzy models and the Maugis-Dugdale contact mechanics [Sitti *et al.*, 2003], but regretfully the process of nanoparticle motion was not analyzed and displayed on the visual interface. And they have also visually simulated the contact interaction based on B-spline based geometry model and Maugis-Dugdale contact mechanics mainly for explaining the sample surface deformation [Vogl *et al.*, 2006], but particle's motion was still not analyzed.

In this research, we will acquire not only 3D interactive force information, but also visual information of MWCNT manipulation process, which are two important aspects in online controlling the assembly process of MWCNT based nano device.

On one hand, for acquiring 3D nano forces information, here the probe's micro- cantilever-tip is used not only as an end effector but also as a nano force sensor for sensing the interactive forces between the probe tip and the sample. With the proposed force model and obtained parameters, 3D nano forces can be obtained by measuring the signals of position sensitive detector (PSD) which reflect probe's cantilever deflections, and then fed to a haptic device after proportionally amplified for operator to feel.

On the other hand, as the unique probe cannot scan the sample at the same time of manipulating, for real-timely displaying the manipulation process, the particle' motion can be modeled and displayed on the visual interface according to virtual-reality (VR) technology. And as physical condition in nano-environment varies much, it is not feasible to build up universally-suitable model for all kinds of particle motion. For that, here only MWCNT's manipulation is discussed and its motion model is proposed, based on which the real-time position and gesture of the MWCNT manipulated can be obtained according to the real-time probe position and applied forces, and then updated on the visual interface to provide operator with online visual information.

Based on real-time force and visual information acquisition and feedback, the operator can online control the manipulation process and the eventual result, by real-timely adjusting the probe's 3D motion and applied forces with the assistance of a haptic device. MWCNT's push and pilot assembly experiments will be performed to verify the effectiveness of the method.

2. Real-Time 3D Nano Force Information Obtainment

2.1. *Modeling 3D nano forces*

During manipulation, the probe tip will be applied by various kinds of nano forces, such as Van der Waals force, capillary force, electrostatic force, repulsive contact force, nano frictional forces and etc. [Israelachvili *et al.*, 1991], and the resultant force of these forces, which causes the cantilever's bend and twisting deflections, can be simplified as 3D forces, namely F_x, F_y and F_z, along coordinate axes as shown in Fig. 1.

In the three forces, the force F_x will twist the cantilever around Y-axis with twisting angle θ_x,

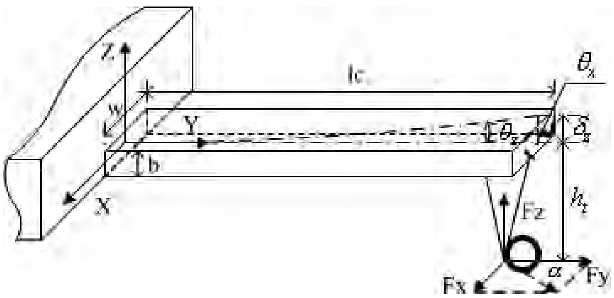


Fig. 1. Model of 3D nano forces dependent on cantilever deflections.

which can be presented as

$$F_x(h_t + b/2) = k_{ct}\theta_x, \quad (1)$$

where h_t is the tip height, b is cantilever thickness, k_{ct} is the cantilever's torsion strength.

The forces F_z and F_y will make the cantilever bend in Y-Z plane with bend deflection δ_z presented as

$$F_z l_c + F_y(h_t + b/2) = k\delta_z l_c, \quad (2)$$

where l_c is the cantilever length, k is the cantilever's force constant.

And as the probe moves with angle α to Y-axis, the relationship between forces F_y and F_x will be

$$F_y = F_x c \tan\alpha. \quad (3)$$

2.2. *Obtaining 3D nano forces according to PSD signals*

After amplified by optical lever, the cantilever's bend deflection δ_z and twisting angle θ_x can be detected by PSD as shown in Fig. 2.

And δ_z and θ_x can be obtained as

$$\delta_z = k_v S_v, \quad (4)$$

$$\theta_x = k_h S_h, \quad (5)$$

where k_v and k_h are system constants, S_v is the vertical PSD signal and S_h is the horizontal PSD signal.

After Eqs. (4) and (5) are submitted into Eqs. (1)–(3), 3D nano forces can be obtained according to PSD signals and be presented as

$$\begin{cases} F_x = k_{ct}k_h S_h/(h_t + b/2) \\ F_y = F_x c \tan\alpha \\ F_z = k k_v S_v - F_y(h_t + b/2)/l_c \end{cases}. \quad (6)$$

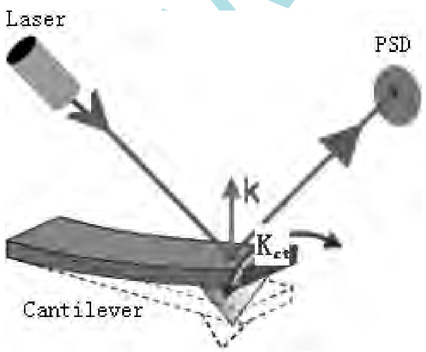


Fig. 2. Cantilever deflections measured by PSD.

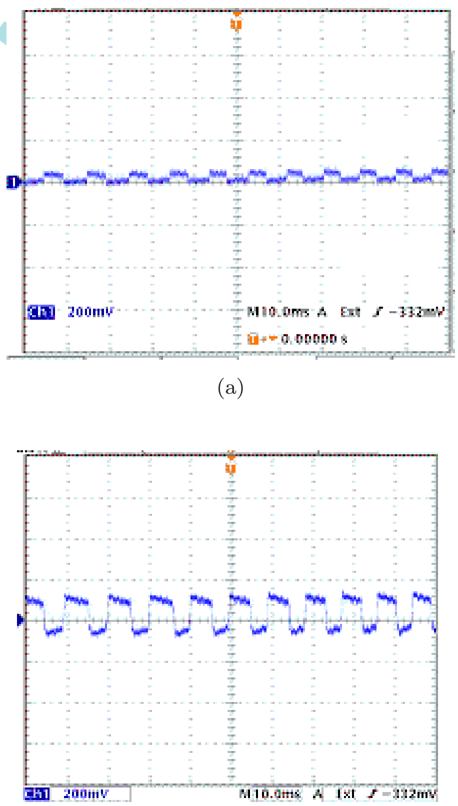
2.3. *Parameters obtainment*

In order to acquire the 3D nano forces, parameters in Eq. (6), such as k_v, k_h, k_{ct} and k, should be obtained.

2.3.1. k_v

Using Z-direction calibration gratings comprising of rectangular steps with calibrated height, move the probe horizontally across the steps with feedback off, the probe will move along the step top to the bottom and the cantilever deflection will the same of the step's height, and record the vertical PSD signal with an oscillograph as shown in Fig. 3.

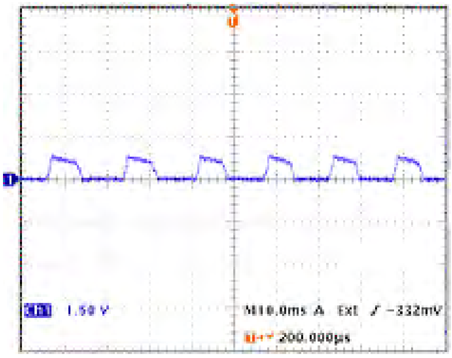
From Fig. 3, it can be seen that the change of vertical PSD signal is 32 mv when step height is 20 nm, while it is 156 mv and 710 mv, respectively to 101.8 nm and 500 nm step, and the dependent curve of vertical cantilever deflection



(a)

(b)

Fig. 3. Vertical PSD signal to different step height (a) step height is 20 nm, (b) step height is 101.8 nm, (c) step height is 500 nm.



(c)

Fig. 3. (*Continued*)

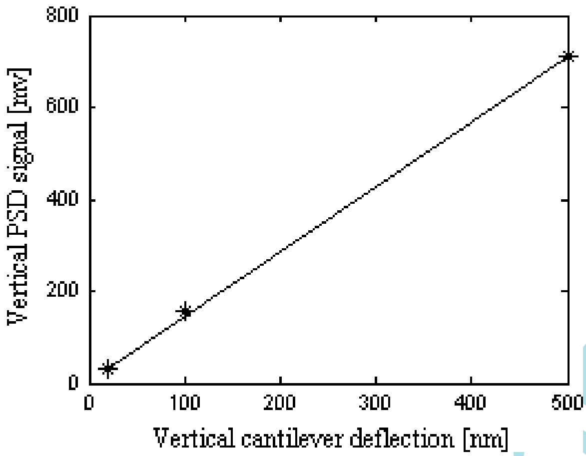


Fig. 4. The dependent curve of vertical cantilever deflection on vertical PSD signal.

on vertical PSD signal can be obtained as shown in Fig. 4.

Noting that $k_v = \delta_z/S_v$, the parameter k_v is the slope of the line shown in Fig. 4, and we can get $k_v = 706\,\mathrm{nm/V}$.

Note that as Z calibration grating (Mickomasch Co.) consists of only three different height steps, here we can only acquire three set of measured values with some regret, for k_v can be more accurate if there are more different height steps.

2.3.2. k_h

As PSD has the same sensitivity both in vertical and horizontal direction, that is to say, the PSD vertical and horizontal signal should be equal if the vertical bend angle equals to the twisting angle. As usually the two angles are very small, there is $\theta \approx \tan\theta$, and the vertical bend angle can be presented as

$$\theta_z \approx \delta_z/l_c = k_v S_v/l_c. \tag{7}$$

Paying attention to $\theta_x = k_h S_h$ in Eq. (5) and the same sensitivity in vertical and horizontal directions, we can obtain that $k_h = k_v/l_c$, and here we get $k_h = 0.00565\,\mathrm{rad/V}$ according to $k_v = 706\,\mathrm{nm/V}$.

2.3.3. k_{ct}

The torsion strength of thin-wall rectangle cantilever can be presented [Case *et al.*, 2002] as

$$k_{ct} = G\beta w b^3/l_c, \tag{8}$$

where G is the shear modulus of the cantilever, w is the cantilever width, β is a constant dependent on the ratio b/w. Here $k_{ct} = 8.56 * 10^{-7}\,\mathrm{Nm/rad}$ can be got.

2.3.4. k

For the accurate force constant of the cantilever is very difficult to be measured, the probe with calibrated force constant is used here, which is $k = 38.6\,\mathrm{N/m}$.

With the parameters obtained, nano forces can be calculated from Eq. (6), then sent to a 3-DOF haptic device after being proportionally amplified, thus the operator can feel 3D interactive forces between the probe and the sample, and online control the forces applied on the probe through the force feedback joystick of the haptic device.

3. Real-Time Visual Information Acquisition of MWCNT Manipulation Process

As MWCNT with relatively larger diameter can be seen as a rigid object during manipulation, its motion behavior which can be verified by AFM scan is still accordant with Newton's mechanics although it suffers various kinds of nano forces. (While to very slim SWCNT or nanowire, its deformation is much complex and should be analyzed by quantum mechanics, molecular dynamics etc. and here this condition will be not be discussed).

Usually, MWCNT is not a perfect cylindrical tube with some radial deformation or some carbon particles adhered on it, it prefers sliding rather than rolling during manipulation (it will roll only when the sample surface is on the atomic-scale flatness and the tube is perfect cylindrical [Falvo, *et al.*, 1999], which means a very small roll resistance force). Thus, as the probe acts on the tube during each manipulation step as shown in Fig. 5, the MWCNT will rotate around a point, which is sliding in essence as shown in Fig. 6.

Where line AB represents MWCNT, F is the force applied by the probe at the point T, f is the average resistant force along the tube axis, and S is the rotation center of the tube during this manipulation step.

As probe acts near the tube's right end as shown in Fig. 6, the torque and force equilibrium equations with minimal force needed to keep equilibrium can be presented as

$$\begin{cases} F(l-s) = \dfrac{1}{2}f(L-s)^2 + \dfrac{1}{2}fs^2 \\ fs + F = f(L-s) \end{cases}. \quad (9)$$

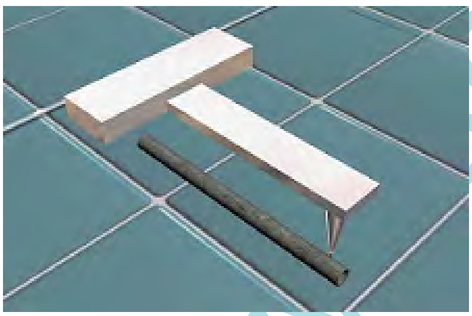


Fig. 5. AFM probe acts on the MWCNT.

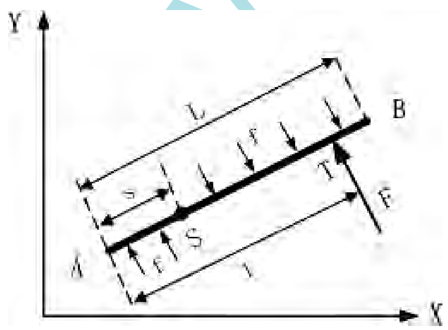


Fig. 6. Rotation motion of MWCNT acted by the probe.

From Eq. (9), the static rotation center during each manipulation step can be deduced as

$$s = l - \sqrt{l^2 - lL + L^2}. \quad (10)$$

Similarly, when probe acts near the tube's left end, similar equilibrium equations can also be obtained.

With the awareness of the tube's two points, which is the rotation center S and the interactive point T decided by the probe position with the compensation of scanner crosstalk error and cantilever deflections [Tian *et al.*, 2005, 2006], the tube's position and gesture during each manipulation can be uniquely determined, and then updated on the visual interface, thus the operator can online adjust the probe's position and motion trajectory to perform MWCNT manipulation.

Obviously, when probe acts at the tube end and vertically to the tube axis, the rotation torque will reach the maximal with the same force and the tube is easier to be moved. Thus, here the manipulation strategy is adopted with the tube's each end pushed alternatively and the probe's motion trajectory will be like character "Z", which is helpful for MWCNT's planar motion. And the later experiments will verify the effectiveness of this manipulation strategy.

4. Experiments Verification

In order to verify the effectiveness of the method described above, an AFM based nanomanipuation system with real-time force and visual information feedback is constructed, and MWCNT's push and pilot assembly experiments will be performed.

4.1. *System configuration*

A sample-scanning AFM, a haptic device and a visual interface are used for imaging and manipulation. The configuration of the AFM based robotic nanomanipulation system is shown in Fig. 7.

In the system, the probe cantilever's deflection signals obtained by PSD, mounted in AFM head, go into the A/D converter card inside

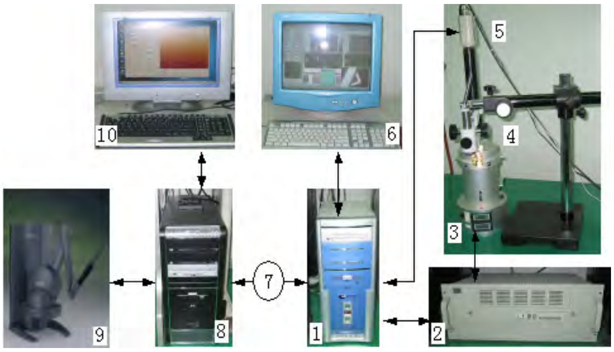


Fig. 7. The configuration of AFM based robotic nanomanipulation system, (1) AFM control computer, (2) CSPM 2000wet controller, (3) AFM head, (4) optical microscope, (5) CCD camera, (6) monitor for imaging and optical vision, (7) Ethernet device, (8) haptic device control computer, (9) 3-DOF haptic device, (10) monitor for viusl interface.

the AFM control computer and are real-timely sent through Ethernet to the haptic device control computer where the forces are calculated. A haptic device is used for 3D nano forces feeling and motion command output through the force feedback joystick. The MWCNT's position and gesture is real-timely updated and displayed on the visual interface. Based on the force and visual feedback, the operator online manipulate the haptic joystick to send command through Ethernet to the AFM control computer, and eventually control the probe's position and motion trajectory and also the magnitude and direction of the applied forces. The robotic manipulation process with real-time force and visual feedback is shown in Fig. 8.

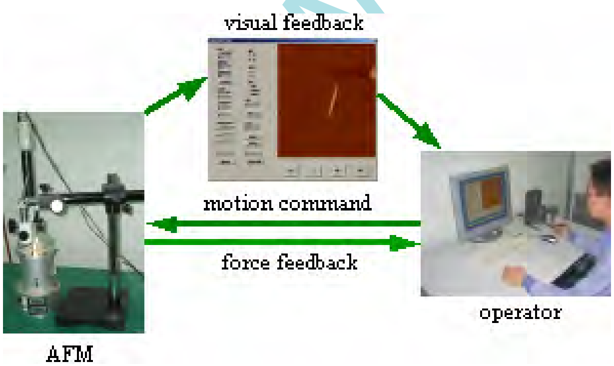


Fig. 8. Robotic nanomanipulation mode with real-time force and visual information feedback.

4.2. *MWCNT push*

After supersonic dispersion in ethanol, MWCNTs are deposited on polycarbonate surface, then a MWCNT is pushed with character "Z" manipulation strategy according to real-time force and visual feedback. Real-time visual display during each manipulation and scan results after each manipulation are shown in Fig. 9.

In Fig. 9, image (a) shows the initial visual interface before manipulation, image (c) shows the first push process real-timely displaying on the visual interface, and image (d) is the corresponding scan result after the first push, images (e) and (f) are respectively visual display and scan result of the second push (where the arrows point to the manipulation position of the probe).

It can be seen in Fig. 9 that the MWCNT is successfully moved, and the visual display is well

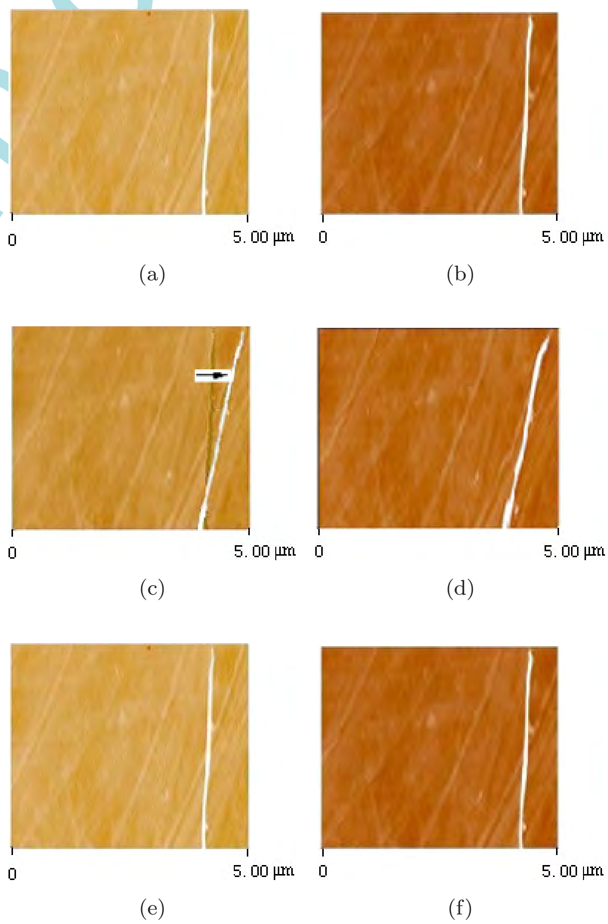
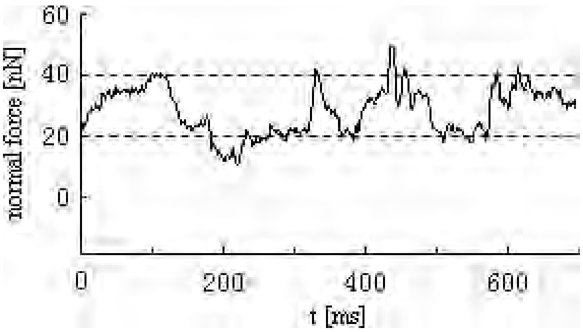
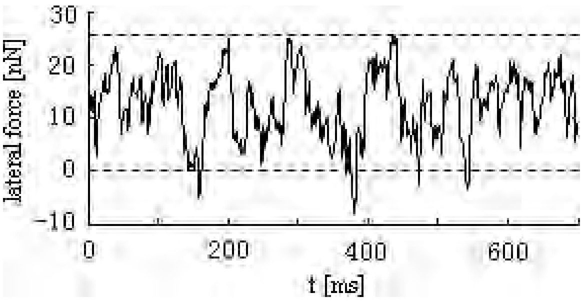


Fig. 9. MWCNT push (a)(c)(e) real-time display on the visual interface, (b)(d)(f) scan result.



(a)



(b)

Fig. 10. Nano forces in the first push (a) normal force, (b) lateral force.

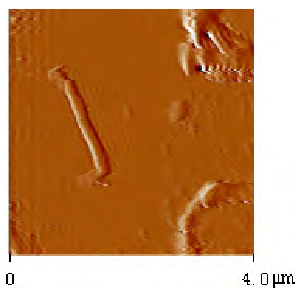
consistent with the scan result. And the controlled forces in the first push are recorded as shown in Fig. 10.

From Fig. 10, it can be seen that the normal force is well controlled at about 20–40 nN with the assistance of force feedback, while the lateral force is controlled at about 0–30 nN with the saw-teeth form corresponding to the MWCNT's "stick-slip" motion.

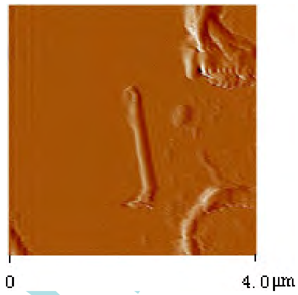
As MWCNT's position and gesture can be real-timely adjusted according to the visual display and force feedback, several steps can be continuously performed, and the manipulation's efficiency and also flexibility can be significantly improved.

5. Pilot Application — MWCNT Assembly

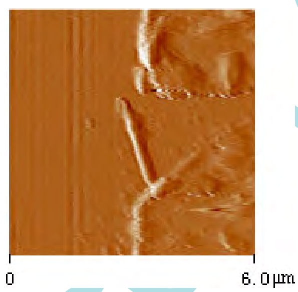
By means of the above AFM based nanomanipulation technology, the selected MWCNT is accurately assembled at the gap of the microelectrode as shown in Fig. 11.



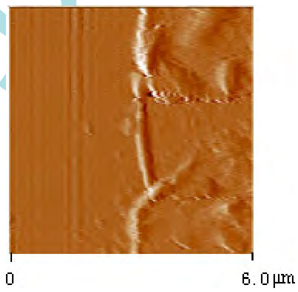
(a)



(b)



(c)



(d)

Fig. 11. MWCNT assembled at microelectrode gap by AFM robotic manipulation (a) before assembly, (b) after several push, (c) one end assembled with microelectrode, (d) after assembly.

After the assembly, the MWCNT's electrical property can be measured and the assembled MWCNT can be pushed off the microelectrode if its electrical property is not suitable, and other suitable MWCNT can be reassembled with the microelectrode, thus it provides a feasible method to select and assemble suitable MWCNT according to its geometrical size and electrical property.

6. Conclusion

In this study, we have presented a method to real-timely acquire force and visual information during MWCNT manipulation process for realizing online control of MWCNT's assembly.

Firstly, AFM probe's micro-cantilever-tip is used as a nano force sensor for measuring the interactive forces between the probe and the sample, that is, 3D nano forces can be calculated according to PSD signals based on the proposed 3D nano force model, and then fed to a haptic device after being proportionally amplified. Secondly, MWCNT's position and gesture are real-timely obtained according to real-time probe position and applied forces based on the proposed MWCNT motion model, and real-timely updated on the visual interface. With real-time force and visual information acquisition and feedback, the operator realized online control of MWCNT's manipulation process by real-timely adjusting the probe's 3D motion and applied forces, and we hope to use this technology to assembly and fabricate MWCNT based nano device.

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Biography

Xiao-Jun Tian received his doctoral degree from Shenyang Institute of Automation (SIA), Chinese Academy of Science (CAS) in 2007, and currently he is an associate professor in Shenyang Institute of Automation, CAS, China. He has jointly accomplished two 863 Projects and has published more than 20 scientific papers. He has received the Excellent Graduate Student Award from the President of CAS in 2006, and 1st-Grade Natural Science Paper Prize of Liaoning Province in 2007 and etc. His major research interests include robotic nanomanipulation, micro/nano systems, nanomanufacture and nanoelectronics.

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