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AFM Based MWCNT Nanomanipulation with Force and Visual Feedback

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To real-timely feel and see the manipulation process of multi-wall carbon nanotube (MWCNT) is required to better control its assembly based on atomic force microscope. Here real-time three-dimensional interactive forces between the probe and the sample can be fed back to the operator according to the proposed force model and position sensitive detector's signals, and MWCNT motion can be online displayed on the visual interface according to probe position and applied force based on the proposed MWCNT motion model and virtual reality technology. Based on force and visual feedback, the process and result of MWCNT manipulation can be online controlled, and MWCNT manipulation experiment will be performed to verify the effectiveness of the method.

Keywords: MWCNT Manipulation, Force and Visual Feedback, Atomic Force Microscope.

1. INTRODUCTION

Atomic Force Microscope (AFM) has been proven to be a useful tool to manipulate materials and structure on the nanometer scale, and several manipulation methods have been proposed.[1–4] However, these manipulation methods can be cataloged into 'scan-design-manipulation-scan' mode, and their main problem is the lack of real-time feedback information, without which the operator can not online control the manipulation process and eventual result, and each manipulation result can only be verified by ceasing the manipulation process to begin a new scan. Obviously this manipulation mode is not flexible and efficient, and the probe is also prone to be worn out due to the lack of force feedback information.

For solving the problem, in this research force and visual information during manipulation will be fed back to the operator for online controlling the manipulation process and eventual result. Firstly, the probe's micro cantilever is used as a nano force sensor to feel the three-dimensional (3D) interactive forces between the probe and the sample during manipulation. And then to real-timely see the manipulation process, as the unique probe can not scan the sample during manipulating, the manipulation process can only be modeled and displayed on the visual interface according to some actual information, such as probe position and applied force, based on virtual reality (VR) technology, which provides the operator with the real-time visual feedback information of manipulation process. Finally, MWCNT manipulation experiment will be performed to verify the effectiveness of the proposed method.

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2. REAL-TIME 3D NANO FORCES FEEDBACK

During manipulation, the probe tip will be applied by various kinds of nano forces,[5] and the resultant force of these forces, which causes the cantilever's bend and twisting deflections, can be decomposed as 3D nano forces, namely F_x, F_y and F_z, along coordinate axes as shown in Figure 1.

With cantilever deflections detected by position sensing detector (PSD), the 3D nano forces dependent on PSD signals can be presented as[6]

$$\begin{cases} F_x = k_{ct} k_h S_h / (h_t + b/2) \\ F_y = F_x c \tan \alpha \\ F_z = k k_v S_v - F_y (h_t + b/2) / l_c \end{cases} \tag{1}$$

where, S_v and S_h are PSD's output signals, and other parameters are parameters of system and probe.

With parameters obtained or calibrated in Eq. (1),[6] 3D nano forces can be calculated and then sent to a haptic device after being proportionally amplified, thus the

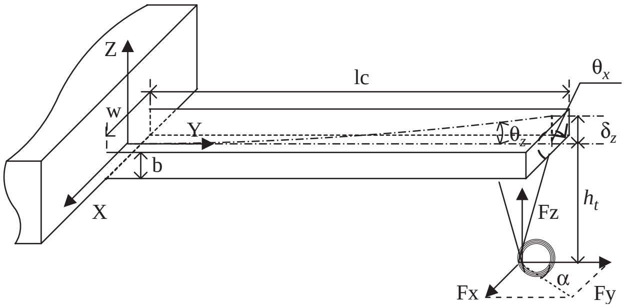

Fig. 1. Model of 3D nano forces dependent on cantilever deflections.

operator can online feel and control the 3D forces by force feedback joystick of the haptic device.

3. REAL-TIME VISUAL FEEDBACK OF MWCNT MOTION

Different to slim SWCNT, usually MWCNT with relatively larger diameter can be seen as a rigid object during manipulation, and its unitary motion behavior, which can be verified by AFM scan, is still accordant with Newton's mechanics although it suffers various kinds of nano forces.

As MWCNT is usually not a perfect cylindrical tube with some radial deformation or some carbon particles adhered on it, it prefers sliding rather than rolling during manipulation, and it will roll only when the sample surface is on the atomic-scale flatness and the tube is perfect cylindrical.[7] Thus, as the probe acts on MWCNT during each manipulation step as shown in Figure 2, the MWCNT will rotate around a point, which is sliding in essence as shown in Figure 3.

where line AB represents MWCNT, F is the force applied by AFM probe at point T, f is the average resistant force along the tube axis, and S is the MWCNT's rotation center during this manipulation step.

As probe acts on MWCNT with minimal force F needed to keep its motion equilibrium, the torque and force

Fig. 2. AFM probe acts on MWCNT.

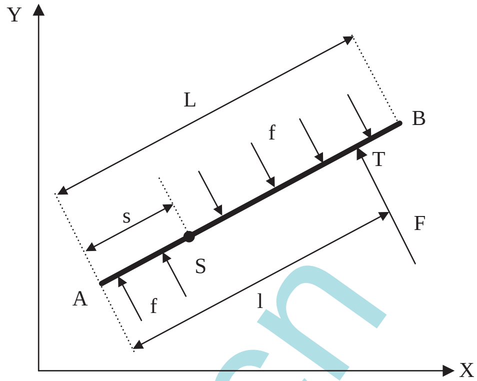

Fig. 3. Rotation motion mode of MWCNT during manipulation.

equilibrium equations can be presented as

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

Then, the rotation center can be deduced as

$$s = l - \sqrt{l^2 - lL + L^2} \tag{3}$$

Similarly, when probe acts near the tube's left end, the rotation center can also be obtained, and then the rotation center can be presented as

$$s = \begin{cases} l + \sqrt{l^2 - lL + L^2}, & l < L/2 \\ l - \sqrt{l^2 - lL + L^2}, & l > L/2 \end{cases} \tag{4}$$

For probe contacts MWCNT during manipulation, the contacting point T on MWCNT is presented by the probe tip position with the compensation of scanner crosstalk error and cantilever deflections.[8,9] With the awareness of the tube's two points, which is the rotation center S and the contacting point T, the tube's position and gesture can be uniquely determined and then real-timely updated on the visual interface according to VR technology. With the real-time visual feedback of MWCNT motion, 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 reaches maximal and the tube is easier to be moved. Here the manipulation strategy is adopted with the tube's each end pushed alternatively and the probe's motion trajectory being character '*Z*,' which is helpful for MWCNT's planar motion and will be experimentally verified.

4. EXPERIMENTS VERIFICATION

In order to verify the effectiveness of the method described above, an AFM based nanomanipuation system with

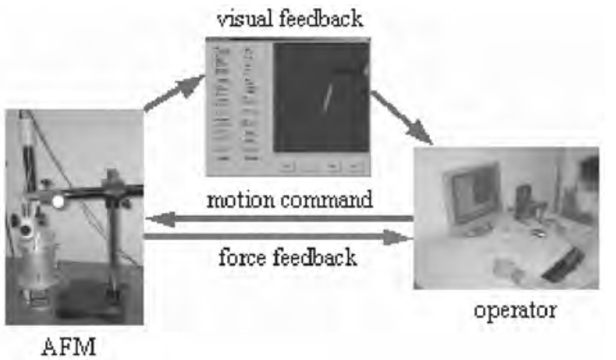

Fig. 4. AFM based nanomanipulation system with real-time force and visual feedback.

real-time force and visual information feedback is built up, and MWCNT manipulation experiment is performed.

4.1. System Configuration

A sample-scanning AFM (model CSPM-2000wet, Ben Yuan Ltd., China) is used for imaging and nanomanipulation. A haptic device is equipped in the system, which is used for 3D force feeling and 3D motion command output through the force feedback joystick. The visual interface is used for real-timely displaying MWCNT's motion and nano-enviroment's change. The system configuration is shown in Figure 4.

Based on the force and visual feedback, the operator can online manipulate the haptic joystick to send motion command through Ethernet to AFM controller, to eventually control the probe's position and motion trajectory and also the magnitude and direction of the applied forces, thus to online perform MWCNT manipulation.

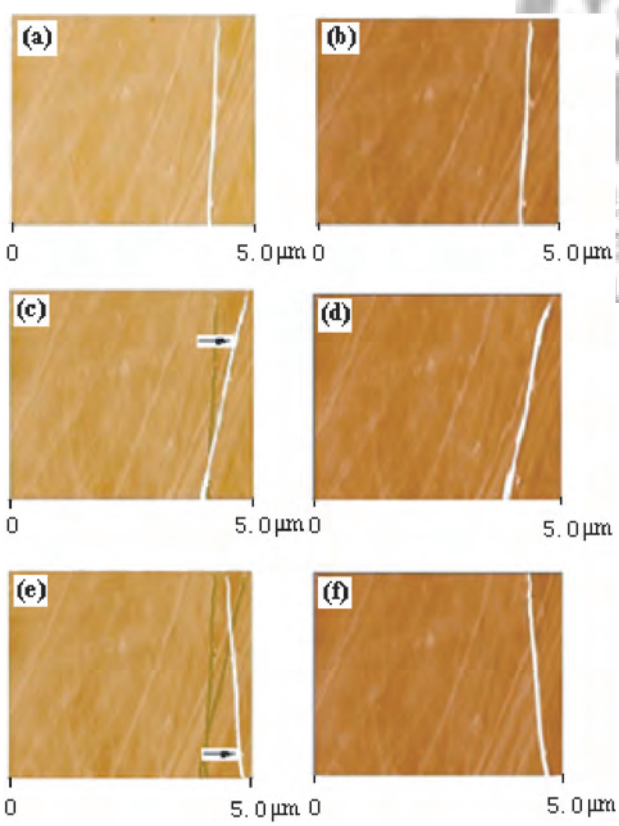

Fig. 5. MWCNT push: (a, c, e) real-time display on the visual interface, (b, d, f) scan result. The arrows point to probe manipulation position.

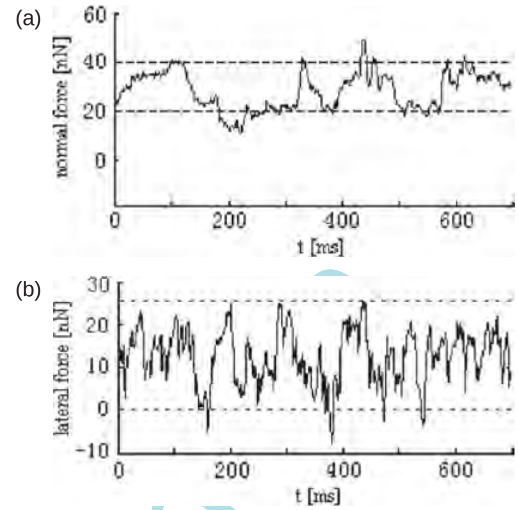

Fig. 6. Nano forces in the first push: (a) normal force, (b) lateral force.

4.2. MWCNT Manipulation

After supersonic dispersion in ethanol, MWCNTs with diameter about 100 nm are deposited on polycarbonate surface, and then one MWCNT is pushed with '*Z*' manipulation strategy according to real-time force and visual feedback as shown in Figure 5.

In Figure 5, image (a) is the initial visual interface display reflecting the initial nano-environment as shown in image (b), image (c) shows the first push process real-timely displayed 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. It can be concluded from Figure 5 that the MWCNT is successfully moved, and the visual display and scan result are well consistent with each other.

During the manipulation, the controlled forces in the first push are recorded as shown in Figure 6.

From Figure 6 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 wave form corresponding to the MWCNT's stick-slip motion.

As MWCNT's position and gesture can be real-timely adjusted according to visual and force feedback, several steps can be continuously performed without stop to scan for each manipulation step, thus the manipulation's efficiency and flexibility can be significantly improved.

5. CONCLUSIONS

In this study, we have presented a method to obtain real-time force and visual feedback information during MWCNT manipulation. Firstly AFM probe is used as a nano force sensor to feel the 3D interactive forces between the probe and the sample. Secondly, MWCNT's position and gesture is real-timely displayed on the visual interface according to the probe position and applied forces based on the proposed MWCNT motion mode and VR technology. With assistance of real-time force and visual feedback information, the operator online controls the process and eventual result of MWCNT manipulation by real-timely adjusting the probe's 3D motion and applied forces during manipulation, and the proposed method provides a new approach to online control the assembly process of MWCNT based nano device.

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