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An AFM Based Nanomanipulation System with 3D Nano Forces Feedback*

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***Abstract* - In the AFM based nanomanipulation, the main problem is the lack of real-time sensory feedback for an operator, which makes the manipulation almost in the dark and inefficient. For solving this problem, the AFM probe micro cantilever-tip is used not only as an end effector but also as a 3D nano forces sensor for sensing the interactive nano forces between the AFM probe tip and the object or substrate in nanomanipulation. In addition, for a sample-scanning AFM even with a strain gauge position feedback sensor for x-y close-loop displacement control of sample stage, scanning size error will still be generated, which is destructive to lateral positioning accuracy of AFM probe. For improving probe lateral positioning accuracy, an error compensating method is adopted according to system error quantitative analysis based on the authors' previous work. With 3D nano forces sensing through a haptic/force device and probe positioning accuracy improvement, the efficiency and accuracy of nano manipulation can be significantly improved. Experiments are presented to verify the effectiveness of the nanomanipulation system.**

Index Terms* - *Nanomanipulation System, 3D Nano Forces Sensing, Lateral Error Compensating of Probe Positioning

I. INTRODUCTION

Atomic Force Microscope (AFM) [1] has been proven to be a useful tool to characterize and change the sample surface down to the nanometer scale. However, in the AFM based nano manipulation [2][3], the main problem is the lack of real-time sensory feedback for an operator, which makes the manipulation almost in the dark and inefficient.

In recent years, several researchers have tried to integrate AFM with haptic technique to assist nanomanipulation [4][5], in which a 1 degree of freedom (DOF) haptic device had been constructed for feeling the vertical force acting on AFM probe tip. However, in one hand, haptic/force feedback technique used by them is very difficult to be implemented due to many unmeasurable forces and parameters in the nano-situation such as Van der Walls force and capillary force, etc. In another hand, horizontal forces acting on tip are ignored, which results in the information shortage for comprehensively feeling nanomanipulation situation and guiding manipulation.

For getting the comprehensive forces information during nanomanipulation, the AFM probe micro cantilever-tip is used not only as an end effector but also as a 3D nano forces sensor for sensing the interactive nano forces between the AFM probe tip and the object or substrate in nanomanipulation. The AFM probe cantilever deflection-force is analyzed for obtaining the 3D nano forces in nanosituation according to real-time PSD signals which reflect the cantilever deflections during nanomanipulation. In 3D nano forces calculation formula, there are several parameters needed to be calibrated, and for in practice it is very difficult and time-consuming to get or calibrate the force parameters according to methods proposed by some researchers [6], [7] etc, a kind of new and relatively easier parameters obtainment or calibration method is also presented in force calculation.

In addition, previous nanomanipulation research was almost implemented with a tip-scanning AFM, where the bow effect only causes vertical cross coupling error in z direction probe positioning which can be ignored for small manipulating area. However, for a sample-scanning AFM even with a strain gauge sensor (SGS) for x-y displacement measurement of sample stage, scanning size error, which is aroused by the thickness difference between the currently manipulated substrate and the calibrated substrate, in x-y horizontal positioning of AFM probe will still be generated for the x-y displacement sensor can only be calibrated for a constant thickness substrate. And this error is destructive to x-y positioning accuracy of AFM probe. For solving the problem, based on the system errors quantitative analysis according to the authors' previous work [8], corresponding compensating method are adopted for minimizing the error. With 3D nano forces sensing through a haptic device and probe positioning accuracy improvement, the efficiency and accuracy of nanomanipulation can be significantly improved. Experiment is presented to demonstrate effectiveness of this nanomanipulation system.

II. 3D NANO FORCES SENSING

A 3D Nano Forces Applied on Cantilever-Tip

During nanomanipulation, the probe tip will be subject to various kinds of nano forces such as Van del Walls force, capillary force, electrostatic force, contact repulsive force,

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frictional force et al. [9], and all these forces applied on tip will make cantilever deflect with bend and twist. The resultant force applied on tip can be simplified as 3D forces, namely F_x, F_y and F_z, along three coordinate axes (X-Y-Z) as shown in Fig. 1.

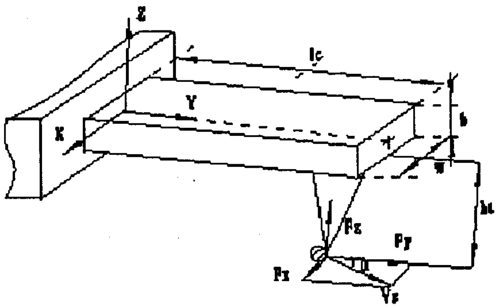


Fig. 1. Model of cantilever-tip subject to 3D nano forces

Since the nanomanipulation task is implemented by the very front part of tip which is very small compared with the whole probe tip body, the forces applied on tip can be viewed as applied on tip apex.

In the three forces, the force F_x will twist the cantilever around its center axis with the twisting angle (θ_x), and it can be obtained by

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

Where, h_t is the height of tip, b is thickness of cantilever, k_{ct} is the torsion strength of cantilever.

The forces F_z and F_y will make the cantilever bend in vertical plane, and the vertical deflection of the cantilever (δ_z) can be presented as

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

Where, l_c is the length of cantilever, k is the force constant of cantilever.

Assume the sample moves relative to cantilever center axis with angle (α), the relationship between forces F_y and F_x will be

$$F_y = F_x c\tan\alpha \qquad (3)$$

With forces applied on tip, the cantilever deflections will happen. The cantilever deflections are detected optically by collecting reflected laser off the cantilever using Position Sensitive Detector (PSD), and the PSD will output signals with vertical signal reflecting the cantilever vertical deflection and horizontal signal reflecting the cantilever twisting deflection. Then δ_z and θ_x can be obtained as

$$\delta_z = k_v S_v \qquad (4)$$

$$\theta_x = k_h S_h \qquad (5)$$

Where k_v and k_h are system constants, S_v is vertical signal output and S_h is horizontal signal output of PSD which can be presented as

$$S_v = \frac{(S_1+S_2)-(S_3+S_4)}{(S_1+S_2+S_3+S_4)}$$

$$S_h = \frac{(S_1+S_4)-(S_2+S_3)}{(S_1+S_2+S_3+S_4)}$$

Where, $S_1 \sim S_4$ are voltage signals output of the quad photodiodes as shown in Fig. 2.

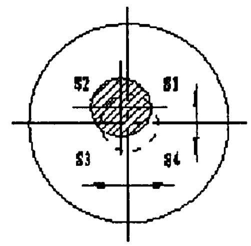


Fig. 2. The quad photodiode detector PSD: $S_1 \sim S_4$ are the signal outputs of the quad photodiodes

With nano forces acting on cantilever-tip analyzed and cantilever deflections obtained by PSD signals, the 3D nano forces can be obtained. Submitting equations (4) and (5) into equations (1)~(3), the 3D forces calculation formulas can be presented as

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

It can be seen from equation (6) that the real 3D forces can be calculated if the parameters (k_{ct}, k_v, k_h and k) can be obtained and calibrated.

B Parameters Obtainment and Calibration

In order to obtain the real forces acting on the tip by measuring the deflection signals from the quad-photodiodes array, the system constants in above equation (6), such as k_{ct}, k_v, k_h and k, must be obtained and calibrated.

1) k_v

Using Z-axis calibration gratings (MickoMasch Inc., USA) comprising an one-dimensional array of rectangular steps with a calibrated height, move the probe horizontally from the above to the bottom of steps with vertical force feedback off, the cantilever deflection will be the height of step, record the PSD vertical signal with an oscillograph (Tektronix TDS3012B, USA) as shown in Fig.3. It is shown in Fig. 3. that PSD vertical signal change is 32mv when step height is 20nm, while it is 156mv when step height is 101.8nm, and 710mv to step height 500nm, then the relationship curve of cantilever vertical deflection δz and PSD vertical signal

S_v can be obtained as shown in Fig. 4.

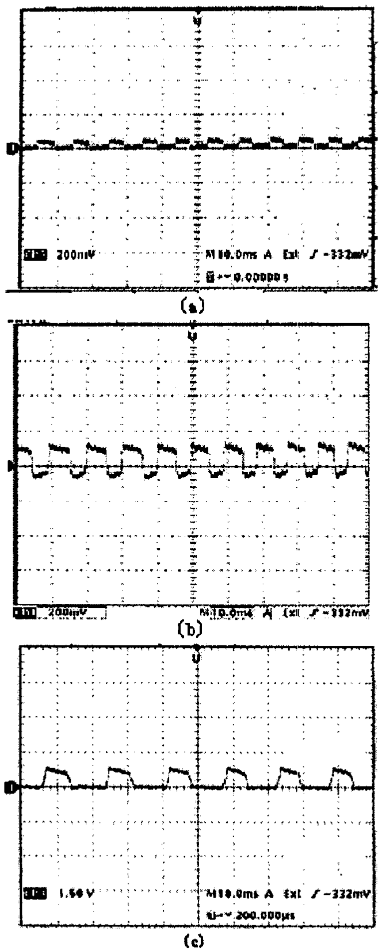


Fig. 3. PSD vertical signal when tip moves on the steps of gratings with different height step while vertical force feedback is off: (a) step height is 20nm; (b) step height is 101.8nm; (c) step height is 500nm

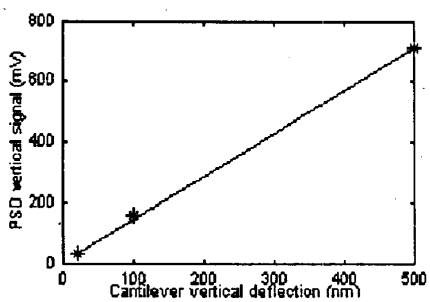


Fig. 4. The relationship curve of the cantilever vertical deflection and PSD vertical signal

The linear relationship between the cantilever vertical deflection and PSD vertical signal is obvious when the deflection is small in Fig. 4.. Noting that $k_v = \delta_z / S_v$, the parameter k_v can be got from the slope of the line as shown in Fig. 4., that is k_v=706nm/V.

2) k_h

For the quad-photodiode detector has the same sensitivity both in the vertical and the horizontal directions in design, that is, the vertical and horizontal signal outputs should be equal if the vertical bending angle equals to the twisting angle. Usually the two angles are very small, there is $\theta \approx \tan\theta$. So, the vertical bending angle can be viewed as

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

Noting that $\theta_x = k_h S_h$ and the same sensitivity both in vertical and horizontal directions, it can be obtained that $k_h = k_v / l_c$, and here we get k_h=0.00565rad/V.

3) k_{ct}

The torsion strength of thin-wall rectangle cantilever can be presented [10] as

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

Where G is the shearing elasticity modulus of cantilever materials which is silicon (100), w is the width of cantilever, β is a constant dependent on b / w [10]. Here k_{ct}=8.56*10^{-7}N.m/rad can be got.

4) k

For the exact force constant k of cantilever is very difficult to get in practice, force constant calibrated probe with k=38.6N/m is used here.

III. LATERAL ERROR COMPENSATING OF PROBE POSITIONING

For a sample-scanning AFM even with a position feedback system based on strain gauge sensor (SGS) for x-y close-loop displacement measurement of sample stage, scanning size error, which is aroused by the thickness difference between the currently manipulated sample and the calibrated sample, in x-y lateral positioning of AFM probe will still be generated for the x-y displacement sensor can only be calibrated for a constant thickness substrate. And this error is destructive to x-y positioning accuracy of AFM probe and must be compensated.

A Kinematics Model and Error Analysis

1) Kinematics Model

In the authors' previous work, the kinematics model of sample-scanning AFM tube scanner and errors analysis have been detailedly described and here it is simply explained as follows.

Supposing that tube scanner material is uniform and its structure is symmetric, when ambipolar voltage is applied to two opposite electrodes of the tube outside wall, and the bend geometry can be viewed as circular arc [11], the kinematics model of the tube scanner is presented in Fig. 5.

In Fig. 5., the part clipped by central angle θ is piezo -ceramics tube, the part pointed by Dss is sample stage, and Dsp is sample, R is the curvature radius of the tube axis, x is the probe tip offset to tube axis.

According to geometrical relationship, the displacement of the scanner (or the point on sample touched by probe tip) can be presented as

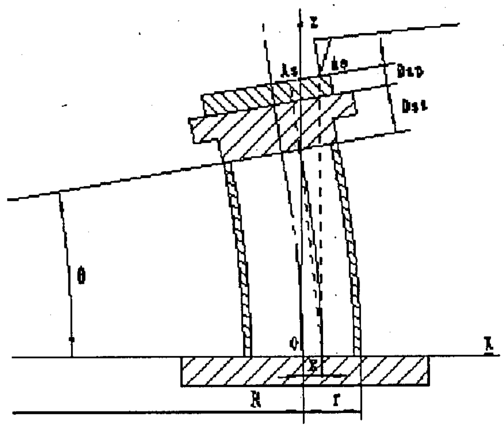


Fig. 5. Kinematics model of single tube scanner in sample-scanning AFM

$$dx = (R+x)(1-\cos\theta) + (Dss+Dsp)\sin\theta \qquad (7)$$

$$dz = ((R+x)\sin\theta - L) + (Dss+Dsp)(\cos\theta - 1) \qquad (8)$$

2) Scanning Size Error

AFM system needs calibration before operating, and the thickness of the grating used in lateral calibration can be called nominal sample thickness ($Dnsp$). After calibration, scanning size can be called nominal scanning size ($Lnss$), which can be easily changed on user interface, and it can be presented as

$$Lnss = 2[R(1-\cos\theta) + (Dss+Dnsp)\sin\theta]/\cos\theta \qquad (9)$$

For $Dnsp$ and Dss are constants, $Lnss$ corresponds to θ or R.

When sample thickness is not equal to nominal one, there will be an error between actual scanning size and nominal one. And scanning size error ($dLss$) between actual scanning size and nominal scanning size can be presented as

$$dLss = 2(Dsp - Dnsp)\tan(\theta) \qquad (10)$$

For $Dnsp$ is a constant, scanning size error ($dLss$) depends on sample thickness (Dsp) and central angle (θ) which corresponds to nominal scanning size ($Lnss$).

B Nanometer Displacement Sensor for Measuring the x-y Displacement of Scanner Sample Stage

According to the model, the displacement sensor for measuring the x-y displacement of scanner sample stage down to 10nm has been combined into the AFM based nanomanipulation system as shown in Fig. 6.

For the x-y displacement sensor can only be calibrated for a constant thickness substrate, when there is a thickness difference between the currently manipulated sample and the calibrated sample, the x-y lateral positioning error of AFM probe will be generated. For minimizing the lateral positioning error, firstly the sample thickness can be increased or decreased to be equal to nominal one in practice. And on those occasions where the special sample's thickness cannot be changed, we can compensate the scanning size error by (10), and here this method is adopted.

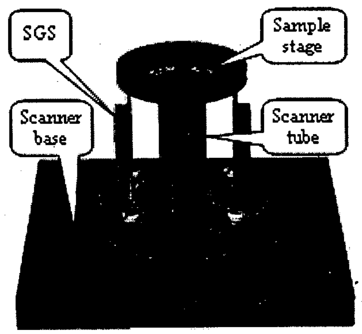


Fig. 6. Nanometer displacement sensor for measuring the x-y displacement of scanner sample stage

IV. EXPERIMENTS AND SYSTEM

In order to verify the effectiveness of the nanomanipulation system, nanolithography is performed and the 3D nano forces are recorded real-time during nanolithography.

A System Configuration

A sample-scanning AFM (model CSPM-2000wet, Ben Yuan Ltd., China) was used for imaging and nanomanipulation. A scanner is equipped in the AFM head with a nanometer displacement sensor for measuring the x-y displacement of scanner sample stage, and its maximum XY scan range is 50umX50um and Z range is 5um. The AFM based nanomanipulation system is shown in Fig. 7.

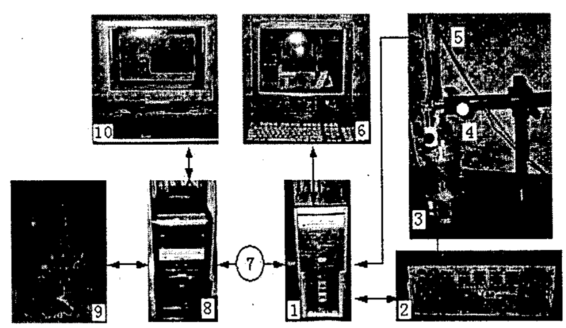


Fig. 7. The configuration of AFM based nanomanipulation system: 1, AFM control computer; 2, CSPM 2000wet controller; 3, AFM head; 4, optical microscope; 5, CCD camera; 6, Monitor for imaging show and optical vision; 7, Ethernet device; 8, Phantom™ control computer; 9, Phantom™; 10, monitor for manipulation interface

In the system, the cantilever deflection signals obtained by PSD, mounted in AFM head, go into the A/D convertor card inside the AFM control computer and are real-time sent through Ethernet to Phantom ™ control computer where the forces are calculated. A Phantom ™ (Sensable Co., USA) is used for 3D nano forces feeling and motion commands input, that is, the forces are felt by operator from Phantom ™ joystick and the motion command is sent through Ethernet into the AFM control computer to control the scanner's motion. The optical microscope and CCD camera help the operator to adjust the laser to focus on cantilever end and search for interesting area on substrate.

B Nanolithography experiment

In this experiment, the surface of a soft material called polycarbonate is lithographed with three characters 'SIA' as shown in Fig. 8., the forces during lithography is fed to Phantom™ and recorded real-time. AFM nano-probe (model NSC15-F5, MickoMasch Inc., USA) with rectangle cantilevers whose force constant has been calibrated is used, and the probe is made of silicon (100) with radius of tip apex about 10nm and full tip cone angle less than 20^0.

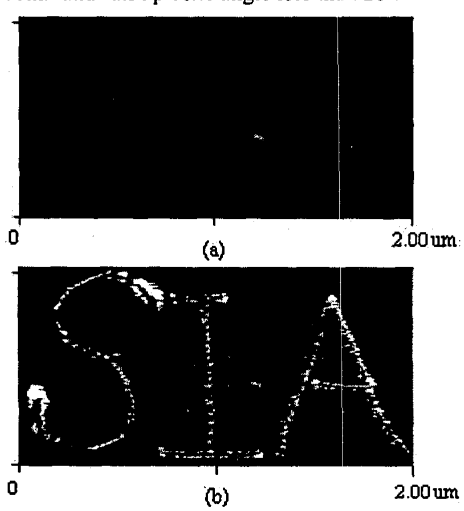
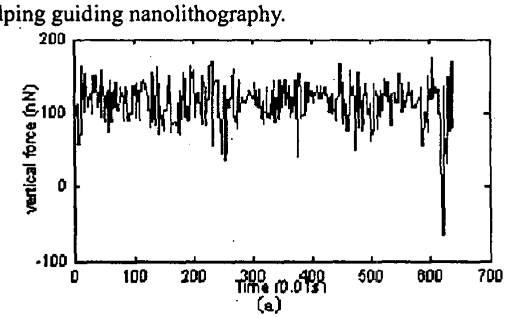


Fig. 8. Nanolithography on polycarbonate: (a) scanning image before nano-imprint; (b) scanning image after nanolithography;

The vertical force and horizontal force along x axis during character 's' lithography are demonstrated as shown in Fig. 9.

From experiments it can be seen that the nanolithography are performed effectively and efficiently in about six seconds for lithographing character 'S', and 3D nano forces are real-time feed to Phantom™, which gives the operator real and comprehensive forces information in nano situation for helping guiding nanolithography.



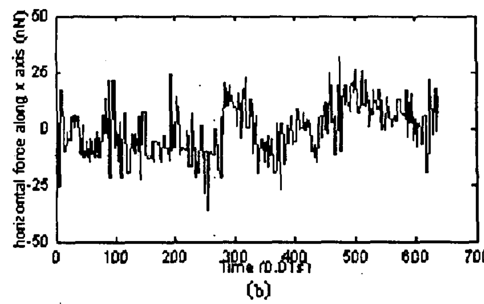


Fig. 9. Forces in nano-imprinting character 'S': (a) vertical force; (b) horizontal force along x axis

V. CONCLUSION

For solving the problem of real-time feedback sensory information shortage in nanomanipulation, the micro cantilever-tip is used as a force sensor to sensing the 3D nano forces applied on AFM probe tip in nano manipulation environment. In addition, for improving the probe x-y positioning accuracy for a sample-scanning AFM with a strain gauge sensor (SGS) for x-y displacement measurement of sample stage, an error compensating method is adopted according to system error quantitative analysis. As a result, the operator can accurately and efficiently conduct nanomanipulation under the assistance of real-time haptic/force feedback. Nanolithography experiments verify the effectiveness and efficiency improvement of nanomanipulation using this nanomanipulation system.

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