3D Nano Forces Sensing for An AFM Based Nanomanipulator[1]

Xiaojun Tian[1,2], Lianqing Liu[1,2], Niandong Jiao[1,2], Yuechao Wang[1] and Zaili Dong[1]
1 Shenyang Institute of Automation, Academy of Sciences, Shenyang 110016, China
2 Graduate School, Academy of Sciences, Beijing 100039, China
xjtian@sia.cn

Ning Xi[1,3]
1 Shenyang Institute of Automation, Academy of Sciences, Shenyang 110016, China
3 Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA

Abstract - **Atomic Force Microscope (AFM) 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, the main problem is the lack of real-time sensory feedback for a user, which makes the manipulation almost in the dark and inefficient. In this paper, the AFM probe micro cantilever-tip is used not only as an end effector but also as a three dimensional (3D) nano forces sensor for measuring the interactive forces between the AFM probe tip and the object or substrate in nanomanipulation. The nano forces acting on cantilever-tip is modeled and the real-time PSD signals are used to calculate the forces. With new parameters calibration method used, the real 3D nano forces can be easily got and then fed to a haptic/force device for operator to feel, thus real-time manipulation forces information is obtained, with which the efficiency of nanomanipulation can be significantly improved. Nano-imprint experiments verify the effectiveness of 3D forces sensing system and efficiency improvement of nano manipulation using this system.**

***Index Terms** – AFM Based Nanomanipulator, 3D Nano Forces modeling, Parameters Calibration*

I. INTRODUCTION

Atomic Force Microscope [1] (AFM) has been proven to be a useful tool to study sample surfaces down to the nanometer scale. Recently, not only can AFM characterize sample surfaces, it can also change the sample surface through manipulation with the AFM probe cantilever-tip as an end effector. One kind of AFM probe with rectangle cantilever and taper tip is shown in Fig.1.[1]

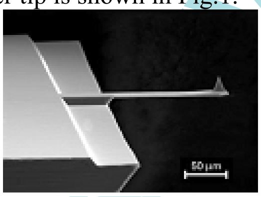

Fig.1 SEM image of AFM probe with rectangle cantilever and taper tip

As the AFM has provided a tool to manipulate materials and structure in the nano scale, various kinds of manipulation methods have been presented in recent years [2][3][4][5]. However, in the AFM based nanomanipulation, main problem is the lack of real-time sensory feedback for an operator, and the manipulation is conducted in the dark. The results can only be verified by another new image scan for every manipulation step. Obviously, this scan-design-manipulation -scan cycle is very time-consuming and inefficient [5].

Recently some researchers have tried to combine the AFM with haptic technique to facilitate nanomanipulation [6][7], in which a 1 degree of freedom haptic device has 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 realized 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 of comprehensively feeling nano manipulation situation and navigating manipulation.

In this paper, for solving the problem described above, the probe micro cantilever-tip is used not only as an end effector, but also as a three dimensional (3D) nano forces sensor for sensing the interactive forces between the AFM probe tip and the object or substrate in nano manipulation. The model of cantilever-tip suffering 3D nano forces is presented and the forces are got according to the model from real-time PSD signals, which reflect the micro cantilever deflections during nano manipulation. New parameters obtainment & calibration method is also presented in force calculation. Then the 3D nano forces are augmented and sent into a haptic/force sensing device for operator to feel. Nano-imprint experiments verify the effectiveness of the 3D nano forces sensing system.

II. 3D NANO FORCES MODELING

A. Analysis of 3D Nano Forces Acting on Cantilever-Tip

During nano manipulation with AFM probe, the cantilever-tip will be subject to various kinds of nano forces such as Van del Walls force, capillary force, electrostatic force, contact repulsive force, frictional force et al. [8], 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 as shown in Fig. 2.

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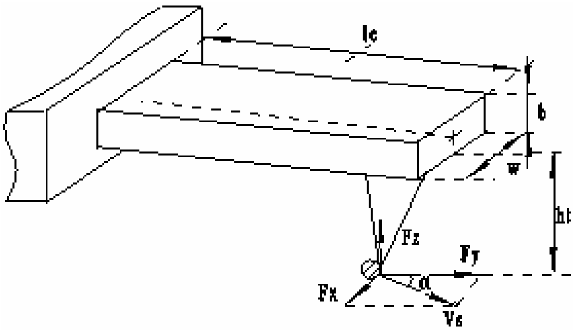

Fig. 2. Model of cantilever-tip subject to 3D nano forces

Since the nano manipulation 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

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

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

$$F_z l_c + F_y(h_t + b/2) = k\delta_z l_c \tag{2}$$

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

$$F_y = F_x c\tan\alpha \tag{3}$$

B. Cantilever Deflections Measurement Using PSD Signals

With forces applied on tip, the cantilever deflections will happen with cantilever vertical bend deflection and twisting angle. The cantilever deflections are detected optically by collecting reflected laser off the cantilever using Position Sensitive Detector (PSD), which consists of four photodiodes to detect the minute changes in light path of laser, and the PSD will output signals with vertical signal reflecting the cantilever vertical deflection and horizontal signal reflecting the cantilever twisting deflection as shown in Fig. 3.

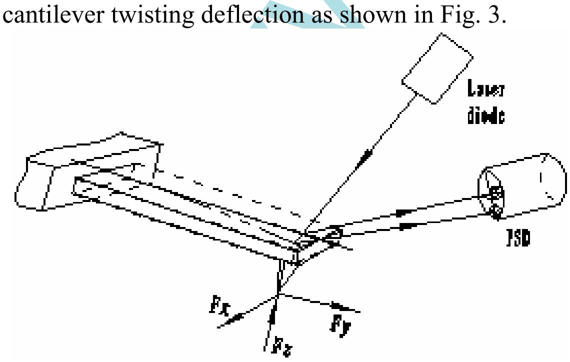

Fig.3. Cantilever deflections measurement using PSD

Then δ_z and θ_x can be obtained as

$$\delta_z = k_v S_v \tag{4}$$

$$\theta_x = k_h S_h \tag{5}$$

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

$$S_v = (S_1 + S_2 - S_3 - S_4)/(S_1 + S_2 + S_3 + S_4)$$

$$S_h = (S_1 + S_4 - S_2 - S_3)/(S_1 + S_2 + S_3 + S_4)$$

Where $S_1 \sim S_4$ are voltage signals output of the quad photodiodes as shown in Fig. 4.

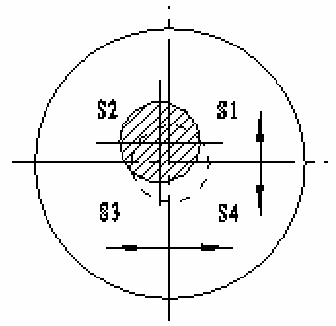

Fig.4. The quad photodiode detector PSD: $S_1 \sim S_4$ are the signal outputs of the quad photodiodes

C. 3D Nano Forces Calculation Formulas

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

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

It can be seen from (6) that the real 3D forces can be got with PSD signals if the parameters can be obtained and calibrated.

III. PARAMETERS OBTAINMENT & 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 (6), such as k_{ct}, k_v, k_h and k, must be obtained and calibrated.

A. 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. 5.

Fig. 5. shows 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. 6.

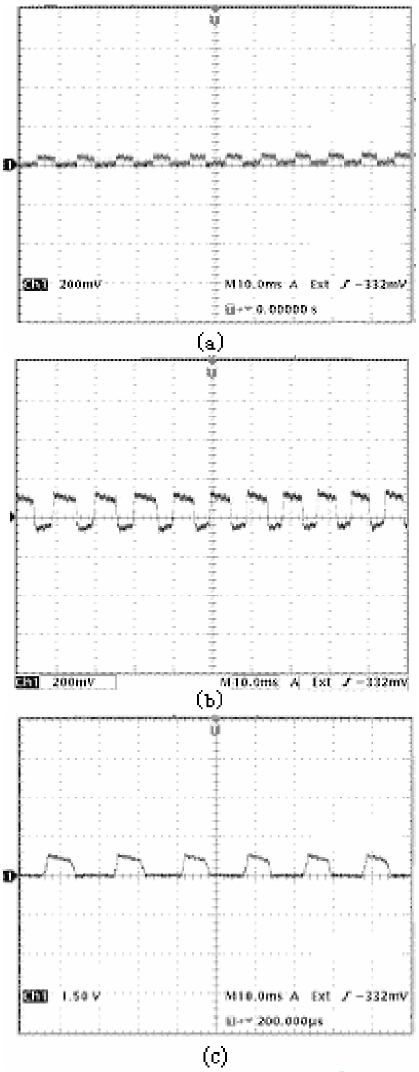

Fig. 5. PSD vertical signal when tip moves on the steps of gratings with different height step while vertical force feedback is off: (a) step height is 20nm; (b) step height is 101.8nm; (c) step height is 500nm

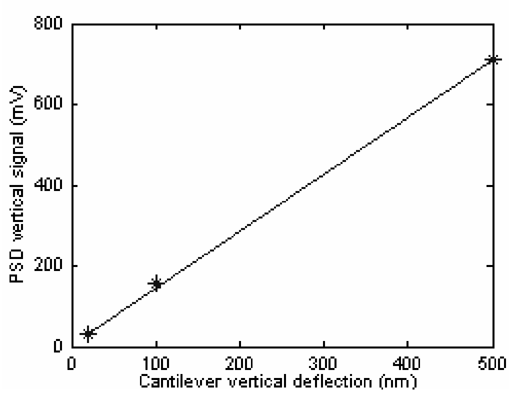

Fig. 6. The relationship curve of the cantilever vertical deflection and PSD vertical signal

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. 6., that is k_v=706nm/V.

B. k_h

For the quad-photodiode detector has the same sensitivity both in the vertical and the horizontal directions in design, i. e., 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

$$\theta_z \approx \delta_z / l_c = k_v S_v / l_c$$

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.

C. k_{ct}

The torsion strength of thin-wall rectangle cantilever can be presented [9] 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 [9]. Here k_{ct}=8.56*10^{-7}N.m/rad can be got.

D. k

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

IV. EXPERIMENT AND SYSTEM

In order to verify the force model presented and the effectiveness of forces sensing system, nano-imprint is performed and the nano forces are recorded real-time during nano-imprinting

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 maximum XY scan range of 50um X 50um and a Z range of 5um.The AFM based nano manipulation system is shown in Fig. 7.

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 the Phantom™ interface computer where the forces are calculated. A Phantom™ (Sensable Co., USA) is used for 3D nano forces feeling and motion commands input, i. e., the forces are felt by operator from the Phantom™ joystick and the scanner motion command produced by joystick 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.

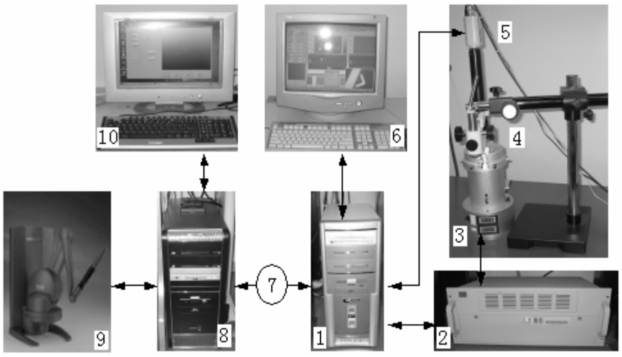

Fig. 7. The configuration of AFM based nanomanipulation system: 1, AFM control computer; 2, CSPM 2000wet controller; 3, AFM head; 4, optical microscope; 5, CCD camera; 6, monitor for imaging and optical vision; 7, Ethernet device; 8, Phantom™ interface computer; 9, Phantom™; 10, monitor for Phantom™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

B. Nano Forces in Nano-imprint

In this experiment, the surface of a soft material called polycarbonate is imprinted with three characters 'SIA' as shown in Fig. 8., the forces during imprint 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.

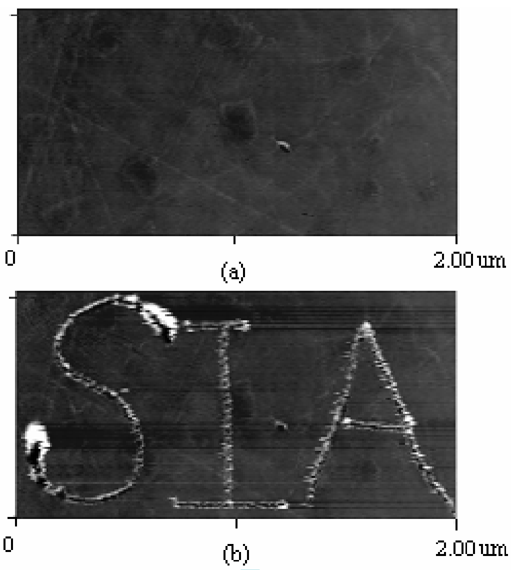

Fig.8. Nano-imprint on polycarbonate: (a) scanning image before nano-imprint; (b) scanning image after nano-imprint;

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

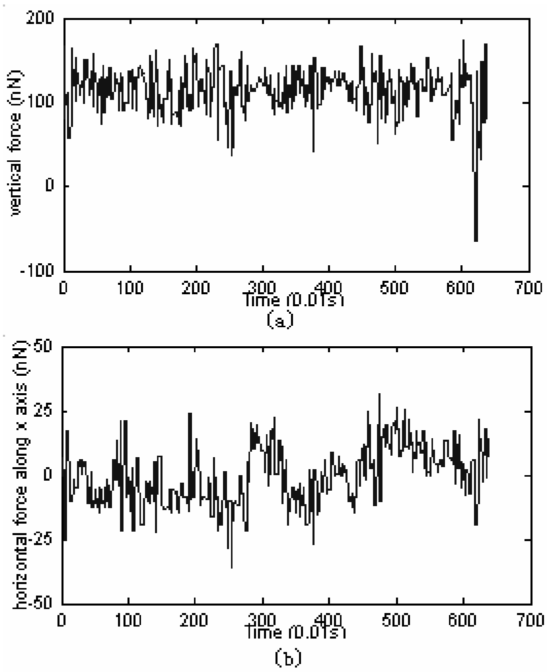

Fig. 9. Forces in nano-imprinting character 'S': (a) vertical force; (b) horizontal force along x axis

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

V. CONCLUSION

For solving the problem of real-time feedback sensory information shortage in nanomanipulation, the micro cantilever-tip is used as a 3D nano forces sensor and the forces are modeled, PSD signals are measured for calculating the real-time forces. With a new method for parameters obtainment and calibration presented in this paper, parameters are relatively easy to be calibrated, thus the real nano forces can be obtained more accurately. Nano-imprint experiments are implemented and the nano forces are feed to a haptic/force device for user to feel, and the effectiveness of 3D forces sensing system and nano manipulation efficiency improvement using this system is verified.

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