Nanoparticle Manipulation Using Atomic Force Microscope and X-Y Stage

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Abstract: Nanotechnology is an important challenge, for which nanoparticle manipulation plays an important role in the assembly of nano elements. In this study, the dynamic equation of system plant is established by van der Waals force, friction, capillary forces etc. To push nanoparticles, strain gauges are used as sensors to actuate an X-Y stage in an atomic force microscopy system. A strategy of pushing nanoparticles is developed based on sliding mode control. Moreover, afuzzy controller is responsible for compensating tip-particle contact loss according to feedback signals of a laser-detector system. According to position control result, experimental results of gold nanoparticle manipulation are presented.

Keywords: Nanoparticle, Nanoparticle Manipulation, AFM, X-Y stage

1. INTRODUCTION

By precise control of atoms, molecules, or nano scale objects, new sensors and man-made materials, tera-byte capacity memories, micro scale robots/machines, DNA computers, quantum devices, micro scale distributed intelligence system devices with integrated sensors, actuators and communication tools, etc., would be possible in the near future. Nanomanipulation in biochemical and medical areas may require experiments to be performed in a liquid environment. Resch and Baur [1] manipulated nano particles using dynamic force microscopy. Resch et al. [2] manipulated gold nanoparticles in liquid environment using the tip of a scanning force microscope for the first time. Hashimoto and Sitti [3] proposed an AFM-based force-controlled pushing system with a manipulation tool (AFM tip) and nano scale object physical interaction for two-dimension positioning of nanoparticles. Since sliding mode control (SMC) has useful invariance properties in the presence of plant model uncertainty and disturbances, this study executes the SMC algorithm to move an XY stage and to compensate crosstalk of XY stage with AFM system. Fuzzy control is utilized to compensate tip-particle contact loss by signals of a laser-detector system, so as to establish an accurate and stable manipulation system.

2. SYTEM MODEL

2.1 AFM Plant

This study deals with an AFM dynamic plant described by

$$\begin{cases} m_{x-eff}\,\ddot{y}_x + b_x\,\dot{y}_x + k_x y_x = \tau_x \\ m_{y-eff}\,\ddot{y}_y + b_y\,\dot{y}_y + k_y y_y = \tau_y - f_{as} \end{cases} \tag{1}$$

where m_{x-eff} and m_{y-eff} are effective masses, b_x and b_y are viscous coefficients , and y_x and y_y are positions of x-axis and y-axis of the XY stage, respectively. $k_x = k_y = 15\times10^6 N/m$ are stiffness coefficients of two PZT translators of the XY scanning stage. τ_x and τ_y are the stage driving force in x-direction and y-direction, and f_{as} is a friction force between the particle and substrate. In Eq. (1),

$$b = 2\xi\sqrt{km_{eff}} \tag{2}$$

$$m_{eff} = \frac{k}{\omega_n^2} \tag{3}$$

where ξ and ω_n denote the damping ratio and natural frequency, respectively. To measure ξ and ω_n , accelerometer equipment and

$$\omega_n = \frac{2\pi f_r}{\sqrt{1-2\xi^2}} \tag{4}$$

are utilized, where f_r is the resonance frequency in the unit of Hz. When the AFM system is knocked by a hammer, impulse response signals transfer from the accelerometer to an amplifier. According to measurement results and calculation of Eqs. (2)~(4), $m_{x-eff} = 0.0905Kg$, $m_{y-eff} = 0.1262Kg$, $b_x = 821.0602Kg/s$ and $b_y =$ 965.9074 Kg/s , $f_{as} = 1.611\times10^{-8}$ N.

As a result, from Eq. (1) the dynamic equation of the AFM system is written as

$$\begin{cases} 0.0904\,\ddot{y}_x + 821.0602\,\dot{y}_x + 15\times10^6 y_x = \tau_x \\ 0.1262\,\ddot{y}_y + 965.9074\,\dot{y}_y + 15\times10^6 y_y = \tau_y - 1.611\times10^{-8} \end{cases} \tag{5}$$

2.2 X-Y scanning stage

In this study, the XY scanning stage produced by NT-MDT firm consists of one flexure stage and two PZT translators. As shown in Fig. 1, the movement is measured with two strain-gauge sensors. Because the piezoelectric translator of the XY scanning stage is the core of actuating element, modeling of the XY stage system has to consist of piezoelectric and mechanical parts. In this study, nanoparticle manipulation is performed at very slow velocity and PZT translator is high-resolution linear actuator. Flexure mechanism and other elements in the XY stage system will be treated as loading of the piezoelectric translator. Since all electric energies are transformed into mechanical energy, a generated mechanical force can be written as

$$F_p = K_p dL(t) \qquad (6)$$

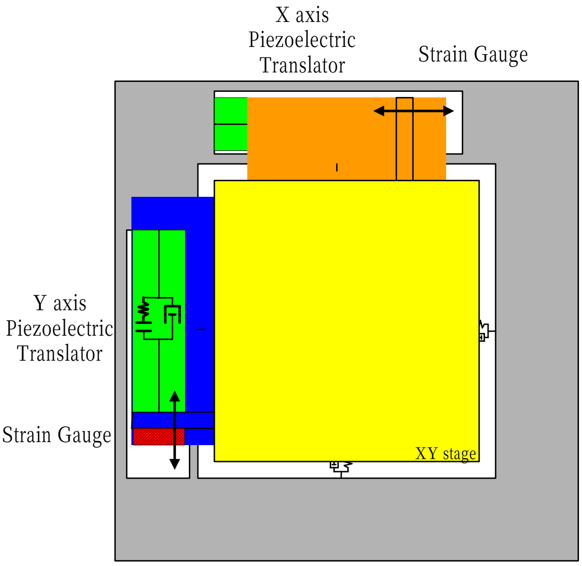


Fig. 1 Modeling of X-Y Stage system

where K_p denotes the spring constant of the piezoelectric translator. dL(t) is the elongation of PZT translator subject to voltage and can be expressed by

$$dL(t) = S_p V(t) \qquad (7)$$

where S_p is a piezoelectric strain constant and V(t) is input voltage. Both piezoelectric translators are in full extension, such that the XY stage is located at the maximum X and Y positions in the initial state. The model of the XY stage system is shown in Fig. 1. From Eq. (6) the mechanical force can be modified as

$$\begin{cases} F_x = k_x dL_x(t) \\ F_y = k_y dL_y(t) \end{cases} \qquad (8)$$

where F_x and F_y are x and y components of generation force of the XY stage, respectively, and k_x and k_y are X-axis and Y-axis spring constants of the XY scanning stage, respectively, and $dL_x(t)$ and $dL_y(t)$ can also be expressed as, from Eq. (2),

$$\begin{cases} dL_x(t) = S_{p-x} V_{p-x}(t) \\ dL_y(t) = S_{p-y} V_{p-y}(t) \end{cases} \qquad (9)$$

where $S_{p-x} = S_{p-y}$ and both are x-axis and y-axis of piezoelectric-strain constants, respectively. Substituting Eq (9) into Eq. (8) yields the XY stage force:

$$\begin{cases} F_x = k_x S_{p-x} V_{p-x}(t) \\ F_y = k_y S_{p-y} V_{p-y}(t) \end{cases} \qquad (10)$$

where S_{p-x} and S_{p-y} can be obtained by measuring displacement and piezo voltage. Measurement results lead to a linear-fit equation written as

$$Y = 3514.4170 + 583.7195V \qquad (11)$$

Using Eqs. (10) and (11) gives $S_{p-x} = S_{p-y} = 583.7195 nm/v$ and $k_x = k_y = 15\times10^6 N/m$. Substituting S_{p-x} and k_x into Eq. (10) yields the XY stage model written as

$$\begin{cases} F_x = \tau_x = 8.7558V_{p-x} + 68.4003 \\ F_y = \tau_y = 8.7558V_{p-y} + 68.4003 \end{cases} \qquad (12)$$

2.3 System plant model

The system plant consists of the AFM dynamic plant and the XY stage system. Hence, substituting Eq. (11) into Eq. (5) yields

$$\begin{cases} 0.0905\,\ddot{y}_x + 821.0602\,\dot{y}_x + 15\times10^6 y_x = 8.7558V_x + 68.4003 \\ 0.1262\,\ddot{y}_y + 965.9074\,\dot{y}_y + 15\times10^6 y = 8.7558V_y + 68.4003 - 1.611\times10^{-8} \end{cases}$$
(13)

Since $68.4003 >> 1.611\times10^{-8}$ in Eq.(13), the term of -1.611×10^{-8} will be ignored and the system plant model can be expressed by

$$\begin{cases} 0.0905\,\ddot{y}_x + 821.0602\,\dot{y}_x + 15\times10^6 y_x - 68.4003 = 8.7558V_x \\ 0.1262\,\ddot{y}_y + 965.9074\,\dot{y}_y + 15\times10^6 y - 68.4003 = 8.7558V_y \end{cases} \qquad (14)$$

Rewriting Eq. (14) by altering the unit of y is from meter to nanometer, the system plant model becomes

$$\begin{cases} 0.0905\times10^{-9}\,\ddot{y}_x + 821.0602\times10^{-9}\,\dot{y}_x + 15\times10^{-3} y_x - 68.4003 = 8.7558V_x \\ 0.1262\times10^{-9}\,\ddot{y}_y + 965.9074\times10^{-9}\,\dot{y}_y + 15\times10^{-3} y - 68.4003 = 8.7558V_y \end{cases}$$

3. PUSHING CONTROL METHOD

This study employs sliding mode control (SMC) [4] for nanoparticle manipulation. SMC has been known as an effective approach to position and velocity control due to its insensitivity to parameter variations and disturbance rejection capability. Hence, this research designs a sliding mode controller as shown in Fig. 2 for nanoparticle manipulation. In practice, a discrete linear time-invariant system has system disturbances and measurement noise. Hence, here a linear quadratic estimator (LQE) [4] is applied to estimate optimal states in the presence of system disturbances and measurement noise.

Fig. 3 depicts the entire control system diagram for pushing nanoparticles. In addition to uncertainty, disturbance and measuring noise, tip-particle contact loss or other operating errors during pushing of nanoparticle also influences plant performance. Therefore, these error sources are compensated by a fuzzy controller [5] in this study.

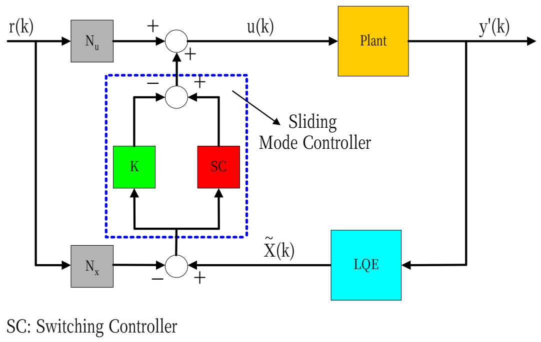


Fig. 2 Sliding mode control with linear quadratic estimator

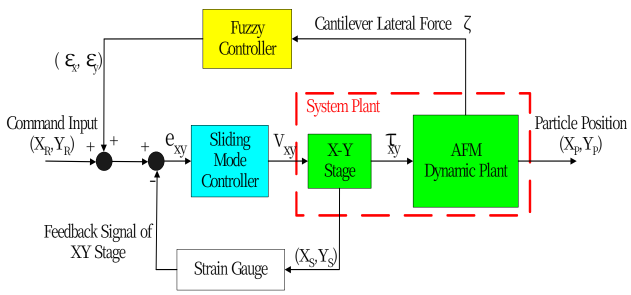


Fig. 3 Control system diagram for pushing nanoparticle

4. SIMULATION RESULTS

For simulation, Fig. 4 shows the flowchart of nanoparticle manipulation with the SMC based on LQE and fuzzy controllers. Assuming command input starts to send at 0.1 sec and tip-particle contact loss occurs at 0.102, 0.12, and 0.136 sec. When tip-particle contact loss occurs, the SMC controller will compensate y-axis position first and then compensate x-axis one. In addition to tip-particle contact loss, static friction sticking also will occur when pushing nanoparticle at the beginning motion, which consists of initial pushing and after tip-particle contact loss. In this study, assuming static friction sticking needs a compensated value of 30 nm. Simulation results by using the MATLAB and Simulink softwares are shown in Figs. 5 and 6, where the solid line is reference command input whereas the dashed line is system output of the stage. The dynamic simulation of nanoparticle manipulation by a software named Working Model is shown in Fig. 7 wherein although contact loss occurs, the probe tip finally pushes a nanoparticle to the destination. Therefore, Figs. 5~7 demonstrate the effectiveness of SMC and fuzzy control. Due to robust properties of the SMC based on LQE, and the compensated effect of fuzzy controller, the system plant with both controllers can achieve the nanoparticle manipulation and establish an accurate and stable manipulation system.

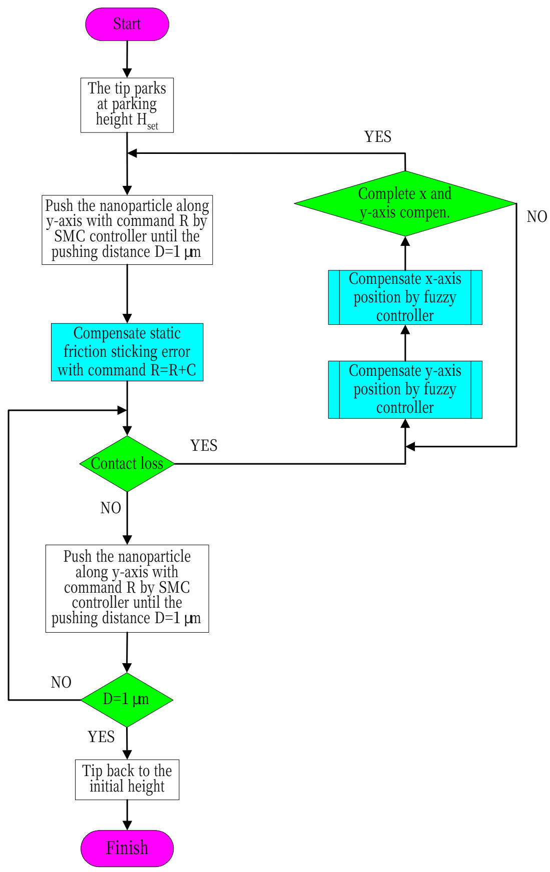


Fig. 4 Flowchart of nanoparticle manipulation

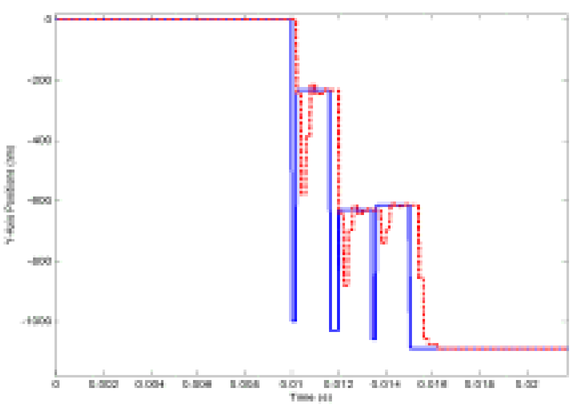


Fig. 5 Command (solid) and simulation results of nanoparticle manipulation along Y-Axis

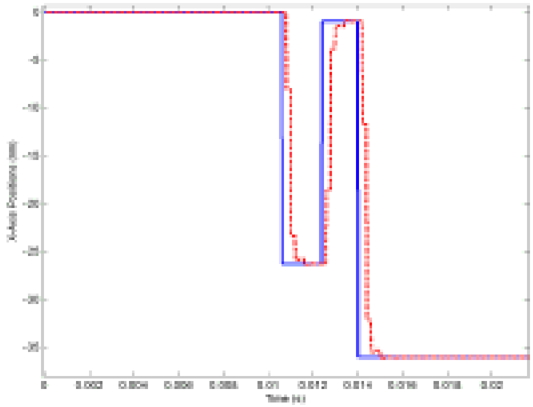


Fig. 6 Command (solid) and simulation r esults (dashed) in X-Axis

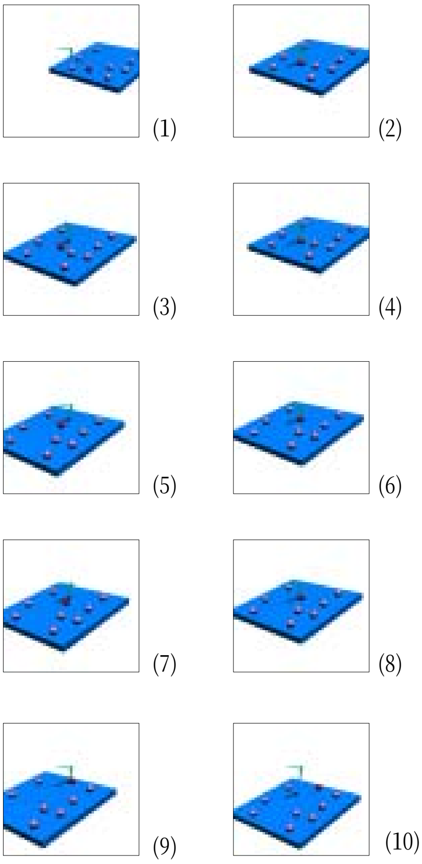


Fig. 7 Ten steps of nanoparticle manipulation

5. EXPERIMENTAL RESULTS

As depicted in Fig. 8, the experimental setup includes PC, Laser Doppler Vibrometer that is used to measure the displacement of the X-Y stage, A/D-D/A card, AFM, and X-Y stage. Experimental results of gold nanoparticle manipulation are depicted in Figs. 9, where 10V input voltage corresponding to 400nm step input command yields consistent displacement output of a nanoparticle. Figs. 9(a) and (b) respectively depict topography before and after manipulation.

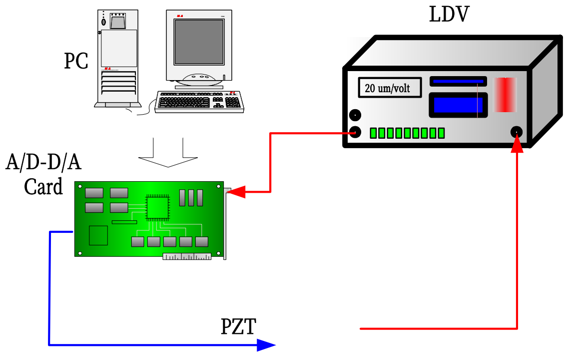
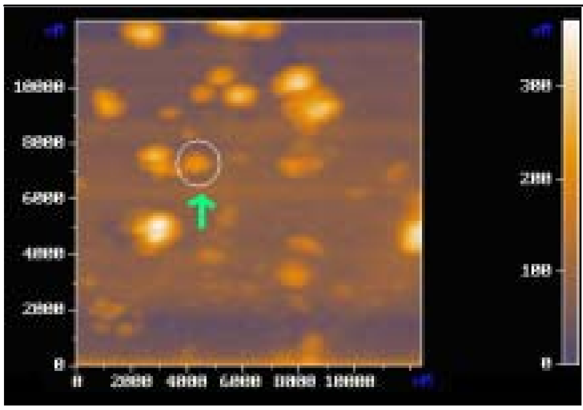
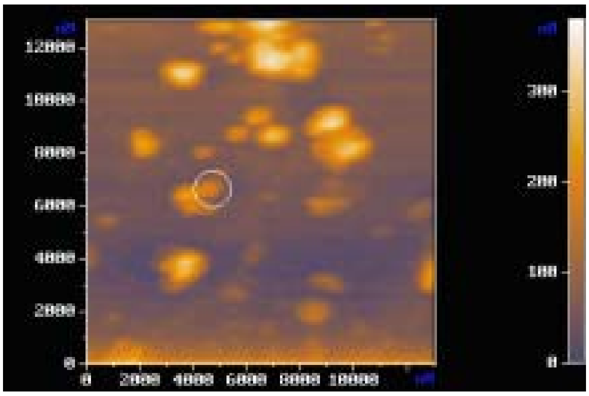


Fig. 8 Atomic force microscopy and X-Y Stage



(a)



(b)

Fig. 9 AFM Topography (a) before and (b) after gold nanoparticle manipulation

6. CONCLUSIONS

The system plant model, comprising an AFM dynamic system and an X-Y stage, has been identified. Simulation and Experimental results have demonstrated performances of stage-position control and nanoparticle manipulation by employing fuzzy control and SMC with LQE observer. In this work, only one-dimensional experiments are carried out. Future work will conduct two-dimensional experiments.

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