

# Sliding Mode Control of AFM in Contact Mode during Manipulation of Nano-Particle

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**Abstract:** Application of atomic force microscope as a manipulator for pushing-based positioning of nano-particles has been of considerable interest during recent years. However a detailed modelling of the interaction forces and control on the AFM tip is important for prosperous manipulation control, a reliable control of the AFM tip position during the AFM-based manipulation process is a main issue. The deflection of the AFM tip caused by manipulation force is the one of nonlinearities and uncertainties which causes difficulties in accurately controlling the tip position, the tip can jump over the target nano-particle then the process will fail. This study aims to design a sliding mode controller (SMC) as robust chattering-free control in contact-mode to control the AFM tip during nano-manipulation process for accomplishment of a precise and effective nano-manipulation task in order to achieve the full automatic nano-manipulation system without direct intervention of an operator. The nano-probe is used to push the spherical micro/nano-particle. Nano-scale interaction forces, elastic deformation in contact areas, and friction forces in tip/nano-particle/substrate system are considered. The first control purpose is controlling and positioning the microcantilever tip at a desired trajectory by the control input force which can be exerted on the microcantilever in the Y direction by a piezo actuator located in the base of the microcantilever. The second control target is PZT-driven positioning stage in AFM-based nano-manipulation in the X,Y in the flat surface. The simulation results show that the designed controllers have been able to make the desired variable state to track specified trajectory during a nano-scale manipulation.

**Keywords:** AFM Nano-Robot, Lyapunov-Based Stability, Nano-Particle Manipulation, Sliding Mode Control

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## 1 INTRODUCTION

Many applications would be possible in near future by precise control of atoms and nano-scale objects such as micro/nano scale robots, machines, computers, surgical instruments and etc. Not only AFM nano-robot is a tool for characterizing surface topography but there is also a strong interest in applying an AFM probe as a nano-manipulator to modify the sample-surface or manipulate nano-structure such as nano-particle. Using AFM as a nano-robot enables us to locate nano-particles in a desired position for micro/nano assembly [1-4]. A Controlled AFM probe as a pushing manipulator is able to positioning the micro/nano-particles in a two dimensional space to build miniaturized structures [2], [5]. So a need for designing a precise controller that guarantees a stable and accurate nano-manipulation task is obvious. Until now, some control schemes have been designed to make the AFM tip track a certain trajectory for the manipulation task.

Delnavaz et al. [5] proposed a combined classical and second order sliding mode to vibration control of the AFM tip in the nano-manipulation tasks, but their nano-manipulation model was simple. Also in [6], a robust adaptive controller for the AFM tip positioning has been designed. The proposed modeling includes coupled dynamics of the microcantilever and piezotube actuator. Uncertainties due to the probe/sample contact are considered in the modeling. Although, various controllers are available to control the AFM probe as a nonlinear system, sliding mode approach is proposed in this paper which displays a satisfactory performance with a simple control structure and it is robustness to model imprecision. Sliding mode controller utilizes a high frequency switching control signal to enforce the system trajectories onto a surface, the so-called sliding surface, after a finite time and remain within the vicinity of the sliding surface towards the equilibrium point thereafter [7].

The sliding surface is designed to achieve desired specifications. The main advantage of the proposed controller, compared to the conventional PID control, is its robustness to variations in its displacement and the environmental conditions. During manipulation, the tip/particle/substrate system experiences a complicated dynamics and a perfect model of the nano-manipulation is useful for the successful control. Some researches have been developed to model the AFM-based nano-manipulation [1], [8-11]. Dynamic behavior of a nano-particle during AFM-based pushing is studied in references [12-13].

This paper is organized as follows: In section 2, the nano-manipulation and its nonlinear mathematical model are described. In section 3, the sliding mode

control for AFM-tip is designed where simulation results are provided too. In addition, in section 4 the dynamic of AFM-surface is proposed, followed by the simulation results demonstrated in section 5.

## 2 MATHEMATICAL MODELLING OF NANO-MAIPULATION

The AFM, which is commonly used as a 3D topography imaging device, is used as a manipulation tool for nano-particle positioning; it consists of a conical tip connected to cantilever probe at the end [1]. A lumped parameters model is used for AFM modeling. Here the microcantilever is modeled as 3 DOFs mass-spring system with total mass  $M$ , inertia moment  $I$ , one torsional and two linear springs, with forces and moment [14]. Normal force  $F_z$ , lateral force  $F_y$  and moment  $M_\theta$  which are proportional to the deflection and the torsion of the microcantilever.

$$K_z = \frac{Ewt^3}{4L^3} \rightarrow F_z = K_z z_c \quad (1)$$

$$K_y = \frac{Ew^3t}{4L^3} \rightarrow F_y = K_y y_c \quad (2)$$

$$K_\theta = \frac{Ewt^3}{6L(1+\nu)} \rightarrow M_\theta = K_\theta \theta \quad (3)$$

The AFM geometry and material property are Young's modulus  $E$ , shear modulus  $G$ , length  $L$ , width  $W$  and thickness  $T$ . The microcantilever is mounted to a piezoelectric actuator with a position sensitive photo detector which receives a laser beam reflected from the end point of the beam to provide microcantilever deflection feedback [14].

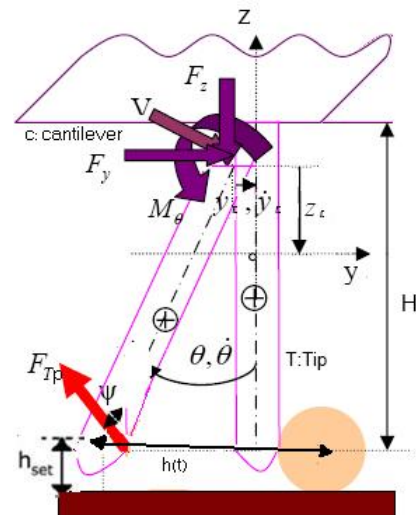


Fig. 1 Free body diagram of AFM lumped parameters model during nano-manipulation [1]

In Fig. 1,  $y_t$  and  $y_c$  are the tip base and the tip apex lateral movements as well as  $z_t$  and  $z_c$  are the tip base and the tip apex vertical movements and  $\theta$  is the tip torsional angle about the x axis. The local coordinates are set up at 'c' and 't' which correspond to the center of the microcantilever cross area and the center of the spherical tip apex. The accelerations of tip apex in normal  $z_t$ , lateral  $y_t$  directions and lateral twisting ' $\theta$ ' can be derived from governing equations on the AFM as:

$$\ddot{z}_t = \frac{1}{(m_t + m_c)} (-F_{tp} \cos \psi - k_z (z_t - \dot{H} \cos \theta) - (\frac{m_t + 2m_c}{2})(\ddot{\theta} \dot{H} \sin \theta + \dot{H} \dot{\theta}^2 \cos \theta)) \quad (4)$$

$$\ddot{y}_t = \frac{1}{(m_t + m_c)} (-F_{tp} \sin \psi - k_y (y_t + \dot{H} \sin \theta) - (\ddot{\theta} \dot{H} \cos \theta - \dot{H} \dot{\theta}^2 \sin \theta) (\frac{m_t + 2m_c}{2})) \quad (5)$$

$$\ddot{\theta} = \frac{1}{(I_t + I_c)} (F_{tp} \cos \psi \dot{H} \sin \theta - k_\theta \theta + F_{tp} \sin \psi \dot{H} \cos \theta) \quad (6)$$

$I_t$  and  $I_c$  are the inertia momentums of the AFM tip and microcantilever through 'c', where  $m_t$  and  $m_c$  are their masses respectively. Also 'H' is the tip height and  $\psi$  is the tip/particle angle. Moreover  $F_{tp}$ , Derjaguin interaction model, is functions of the separation distance of the tip/ particle  $h(t)$  and  $\psi$ , they can be derived based on the geometric features of Figure 1 [13], [14].

The nano-particle is assumed as an elastic spherical object. Free body diagram of nano-particle is depicted in Figure 2. The motion equation of the nano-particle in the y direction and the balancing equation in the z direction for the nano-particle can be written as follow:

$$\ddot{y}_p = \frac{1}{m_p} (F_{tp} \sin \psi - \text{sign}(\dot{y}_p) F_{frict}) \quad (7)$$

$$F_{ps}(t) = F_{tp}(t) \cos \psi + A_{ps}^{adh} \quad (8)$$

$$A_{ps}^{adh} = \frac{H_{ps} R_p}{6a_0^2} \quad (9)$$

Where  $\ddot{y}_p(t)$  is the nano-particle acceleration,  $F_{tp} \sin \psi$  is the tip/particle lateral interaction force which we denominate pushing force and  $F_{frict}$  is the nanoscale friction force on the contact surface of the particle/substrate.

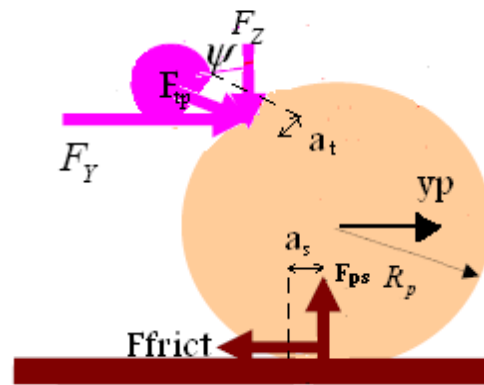


Fig. 2 Dynamic model of the nano-particle which experiences interaction forces and friction force during manipulation [1]

All system parameter values are defined as in [1], and [14].

### 3 DESIGN CONTROLLER

This section devotes to explain and design a sliding mode controller [15]. Purpose of the controller is to maintain the tip at a constant angle above the sample surface while stage moves laterally and tip manipulates the target nano-particle by exerting direct pushing force in the Y direction by a piezo actuator located in the base of the microcantilever. Sliding mode controller is used as a robust chattering-free controller in contact-mode for accomplishment of an effective nano-manipulation task in order to achieve full automatic nano-manipulation system without direct intervention of an operator. We have to make an appropriate assumption about the main parameters of the system to design the controller. The nonlinear system of concern is represented by:

$$\dot{y} = F(Y) + G(Y)U \quad (10)$$

In this work, the number of state variables are eight. They are  $\theta, y_t, y_p, z_t$  and their derivatives;  $\frac{dy_1}{dt} = \dot{\theta} = y_5, \frac{dy_2}{dt} = \dot{y}_t = y_6, \frac{dy_3}{dt} = \dot{y}_p = y_7, \frac{dy_4}{dt} = \dot{z}_t = y_8$  and the number of the control input is one. Finding a proper sliding surface for such a system is not a routine task.

$$\frac{dy_5}{dt} = \ddot{\theta} = \frac{1}{(I_t + I_c)} (F_{tp} \cos \psi \dot{H} \sin y_1 + F_{tp} \sin \psi \dot{H} \cos y_1 - k_\theta y_1 + U)$$

$$\frac{dy_6}{dt} = \ddot{y}_t = \frac{1}{(m_t + m_c)} (-F_{tp} \sin \psi - k_y (y_2 + \dot{H} \sin y_1))$$

$$\begin{aligned}
 & -\left(\frac{dy_5}{dt} \dot{H} \cos y_1 - \dot{H} \dot{y}_1^2 \sin y_1\right) \left(\frac{m_t + 2m_c}{2}\right) \\
 \frac{dy_7}{dt} = \dot{y}_p &= \frac{1}{m_p} (F_{tp} \sin \psi - \text{sign}(\dot{y}_p) F_{frict}) \\
 \frac{dy_8}{dt} = \dot{z}_t &= \frac{1}{(m_t + m_c)} (-F_{tp} \cos \psi - k_z (z_t - \dot{H} \cos y_1) \\
 & - \left(\frac{m_t + 2m_c}{2}\right) \left(\frac{dy_5}{dt} \dot{H} \sin y_1 + \dot{H} \dot{y}_1^2 \cos y_1\right)
 \end{aligned} \tag{11}$$

The sliding surfaces of this system can be defined as:

$$e_1 = \theta - \theta_{set} \tag{12}$$

$$e_2 = y_t - y_{t.set} \tag{13}$$

$$s_1 = \dot{\theta} + \lambda_1 e_1 \tag{14}$$

$$s_2 = \dot{y}_t + \lambda_3 e_2 \tag{15}$$

In Eqs. (12, 13)  $e_1$  and  $e_2$  are errors. To have a stable system with stability guarantee, the lyapunov function is considered as follows:

$$V = |s_1| + \lambda_2 |s_2| \tag{16}$$

$\lambda_2$  is a positive variable defined real number between 0 and 1.

$$\dot{V} = \text{sign}(V) \tag{17}$$

The derivative of (17) is given by:

$$\dot{V} = \frac{s_1 \dot{s}_1}{|s_1|} + \lambda_2 \frac{s_2 \dot{s}_2}{|s_2|} = \text{sgn}(s_1) \dot{s}_1 + \lambda_2 \text{sgn}(s_2) \dot{s}_2 \tag{18}$$

Taking  $\dot{s}_1 = \dot{y}_5 + \lambda_1 \dot{e}_1 = F_1(y) + G_1(y)U + \lambda_1 y_5$  and  $\dot{s}_2 = \dot{y}_6 + \lambda_3 \dot{e}_2 = F_2(y) + G_2(y)U + \lambda_3 y_6$ ,  $U$  is presented by (19). Saturation function is proposed instead of sign function ( $\dot{V} = -\eta \text{sat}(V/\varphi)$ ) for improving the control behavior of AFM tip angle and displacement, and reducing chattering phenomenon as it is shown in Figures 3, and 4. The control objective is to choose  $U$  to make  $\theta$  and  $y_t$  track  $\theta_{set}$  and  $y_{t.set}$  respectively. Using the Lyapunov-based stability, the control signal  $U$  as a force input control is presented as follows:

$$\begin{aligned}
 U = & \\
 & \frac{-\eta \text{sat}(V/\varphi) - (F_1(y) + \lambda_1 y_5) \text{sgn}(s_1) - \lambda_2 (F_2(y) + \lambda_3 y_6) \text{sgn}(s_2)}{G_1(y) \text{sgn}(s_1) + \lambda_2 G_2(y) \text{sgn}(s_2)}
 \end{aligned} \tag{19}$$

Where  $F_1, F_2$  and  $G_1, G_2$  are nonlinear function in (10) for two different sliding surfaces ( $s_1, s_2$ ).

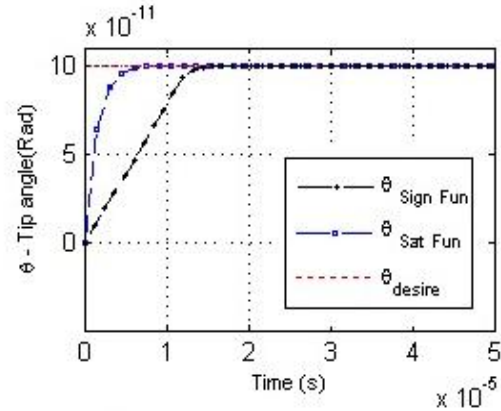


Fig. 3 The angle of AFM tip after control with SMC

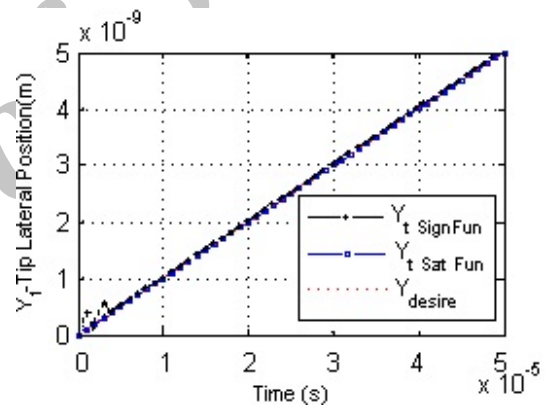


Fig. 4 The displacement of AFM tip during manipulation after control with SMC

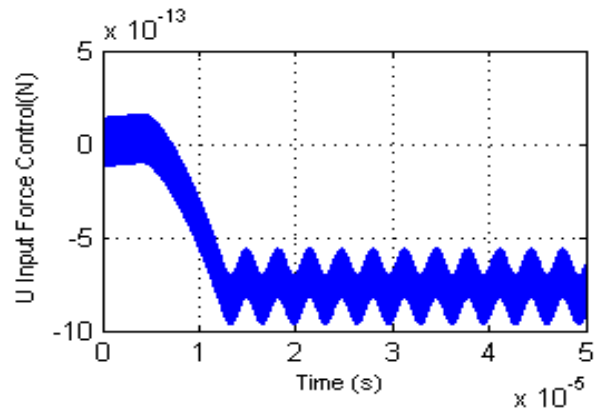


Fig. 5 The Input force control with sign function

Figures 3-5 shows the drastic chattering during the sliding phase can be decreased by using a saturation function instead of assign function in the discontinuous control part. The proposed sliding mode controller in

presence the disturbance leads the tip angle, that is the one of the nonlinearities, to the desired trajectory, also tip and microcantilever move together with the same velocity during nano-manipulation. As a result the tip cannot jump over the target nano-particle and the process will be continued until the end.

**Table 1** Values of the controller used in simulation

Parameter	Value	Parameter	Value
	1e+8	$\varphi$	1e-5
	1e-1	K	1.8e+7
	9e+9	-----	-----

#### 4 DYNAMIC OF SURFACE MODEL

Recently, micropositioning stages have become a highly active research point due to the fact that they are indispensable for handling of objects in micro- or nano-scale. The object of current study is to design a suitable controller based on system dynamic. By denoting the sample position on  $x, y,$  and  $z$  directions as  $x_s, y_s, z_s$  respectively, the dynamics of the stage along each axis are given as in [16].

$$\frac{1}{w_x^2} \ddot{x}_s + \frac{1}{w_x Q_x} \dot{x}_s + x_s + f_{ps}(z_s, z_{sub}) \cos \gamma = \tau_x \quad (20)$$

$$\frac{1}{w_y^2} \ddot{y}_s + \frac{1}{w_y Q_y} \dot{y}_s + y_s + f_{ps}(z_s, z_{sub}) \sin \gamma = \tau_y \quad (21)$$

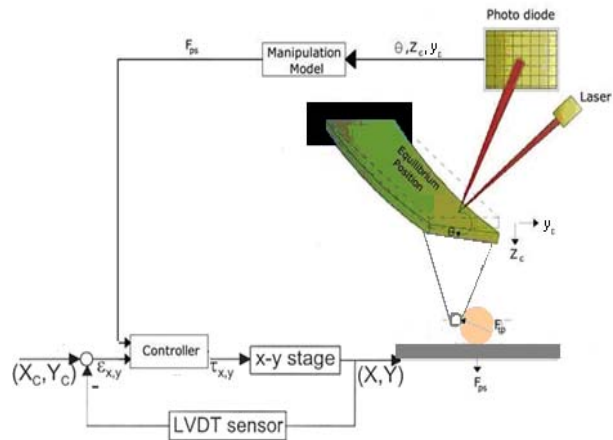
$$\frac{1}{w_z^2} \ddot{z}_s + \frac{1}{w_z Q_z} \dot{z}_s + z_s + F_{ps}(z_s, z_{sub}) \sin \gamma = \tau_z + A_{ps} \quad (22)$$

$$f_{ps} = \mu_{ps} F_{ps} \quad (23)$$

Where  $w$  is the resonant frequency,  $Q$  is the amplification factor,  $f_{ps}$  is frictional force,  $\mu_{ps}$  is the particle-substrate sliding friction coefficient,  $F_{ps}$  denote the particle-substrate interaction force and  $\tau$  is the stage driving forces. A force controller will be designed such that it will change the horizontal position  $x_s, y_s$  of the stage from A to B, while  $z_s$  is at a desired value and constant. This will ensure that the tip contacts the particle with almost the same height away from the substrate during the pushing while minimizing the chance of losing contact with the particle. This requirement also guarantees that a proper force will be applied on the sample without damaging it. The main control aim is to design a control input that guarantees a desired stage motion during nano-manipulation in the X,Y directions and applied force on the cantilever.

#### 5 DESIGN CONTROLLER FOR SURFACE

In this section, a sliding mode controller for the motion from the (0,0) point to (0.5μm,0.5μm) position was designed and compared with previous work [3]with another controller.



**Fig. 6** Control scheme for positioning the cantilever tip during lateral nano-manipulation

$$e_s = \begin{bmatrix} x_s \\ y_s \end{bmatrix} - \begin{bmatrix} x_d \\ y_d \end{bmatrix} \quad (24)$$

$$\begin{bmatrix} \dot{s}_x \\ \dot{s}_y \end{bmatrix} = \dot{e}_s - \lambda e_s \quad (25)$$

$$\begin{bmatrix} \tau_x \\ \tau_y \end{bmatrix} = \left( \begin{bmatrix} -k \operatorname{sgn}(s_x) \\ -k \operatorname{sgn}(s_y) \end{bmatrix} - \lambda \begin{bmatrix} \dot{x}_s \\ \dot{y}_s \end{bmatrix} - F - D \right) / G \quad (26)$$

$[x_s, y_s]^T$  define the system state,  $[x_d, y_d]^T$  are the desire trajectory for the stage and  $[\tau_x, \tau_y]^T$  is the control input vector. F, G are in Eq. (10).The disturbance was denoted as:

$$D = -\alpha + 2\alpha * rand \quad (27)$$

Comparison of the efficiency of the two controllers applied on the AFM-stage system dynamics have shown successful trends in controlling the output of the nonlinear AFM-stage system. The striking feature of sliding mode control is its robustness with respect to F and G. We only need to know the upper bound during the sliding phase, where the motion is completely independent of F and G. Also, the output signal achieves good tracking of the desired reference signal with a better settling time. Now the step responses are tested with three different parameters  $\lambda$ .



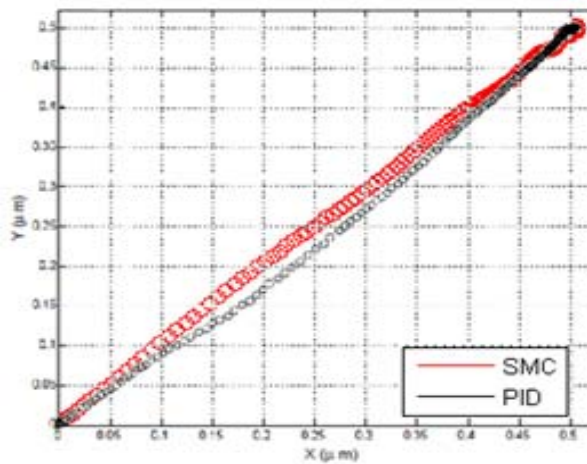


Fig. 7 Comparison control motion of nano-particle from the (0,0) point to (0.5µm,0.5µm) position during pushing to validate the presented sliding controller

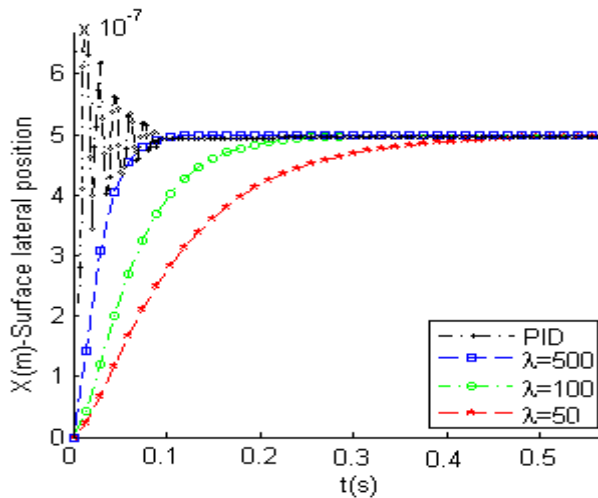


Fig. 8 Comparison step responses of the designed sliding mode controller and PID

This control algorithm is based on Lyapunov technique which is able to provide the stability of the system during tracking a path. The lyapunov function and sliding condition is considered as follows [15]:

$$V = \frac{1}{2}s^2 \rightarrow \frac{1}{2} \frac{d}{dt} s^2 \leq -\eta|s| \tag{28}$$

Table 2 Values of the controller used in simulation

Parameter	Value	Parameter	Value
		50	$\phi$ 1e-10
		1e+2	k 2e-13
		5e+2	

Simulation results in figure 8 show that the design parameters for the sliding mode control influences the shape of the step response. For example, as the parameter  $\lambda$  increasing from 50 to 500, the settling time

is shortened greatly. Thus,  $\lambda=500$  is set in the subsequent simulations, which results in a better step response than PID control.

## 7 CONCLUSION

In this paper, the sliding mode approach is applied to AFM in order to control and surpass the vibration behavior of the AFM micro cantilever by the control input force which can be exerted on the microcantilever by a piezo actuator located in the base of the microcantilever and the stage in the flat surface for the 2D lateral manipulation task. First a reliable model of the pushing based manipulation of nano-particle by an AFM probe is presented. Moreover the paper compared the result of PID controller with the designed SMC. The simulation results demonstrate that the proposed controllers are able to perform the pushing task successfully in term of tracking. It is seen that, the proposed method decreases the effect of disturbance by improving the reaching time.

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## REFERENCES

- [1] Tafazzoli, A., and Sitti, M., "Dynamic behavior and simulation of nanoparticle, Sliding during nanoprobebased positioning", In Proc. of IMECE04, ASME International Mechanical Engineering Congress, Anaheim CA, November 2004.
- [2] Sitti, M., and Hashimoto, H., "Two-Dimensional fine particle positioning under optical microscope using a piezoresistive cantilever as a manipulator", Journal of Micromechatronics, Vol. 1, No. 1, 2000, pp. 25-48.
- [3] Sitti, M., "Teleoperated 2-D micro/nano-manipulation using atomic force microscope", PhD. thesis, University of Tokyo, Japan 1999.
- [4] Jalili, N., and Laxminarayana, K., "A review of atomic force microscopy imaging systems: application to molecular metrology and biological sciences", Mechatronics, Vol. 14, 2004, pp. 907-945.
- [5] Delnavaz, A., Jalili, N., and Zohoor, H., "Vibration control of AFM tip for nano-manipulation using combined sliding mode approach", Proceeding of 7th IEEE international conference on nanotechnology, Hong Kong, August 2007.
- [6] El Raifi, K., El Raifi, O., and Toumi, K. Y., "Modeling and control of AFM-based nano-

- manipulation systems”, Proceedings of the IEEE International Conference on Robotics and Automation, 2005, pp. 157-162.
- [7] Zinober, A. S. I., (Ed.), “Variable Structure and Lyapunov Control”, ‘Lecture notes in control and information sciences’ Springer-Verlag, Berlin, 1994.
- [8] Tafazzoli, A., Pawashe, C., and Sitti, M., “Atomic force microscope based two-dimensional assembly of micro/nanoparticles”, in proc. of IEEE Conf. on nanotechnology 2005.
- [9] Korayem, M. H., and Zakeri, M., “Dynamic modeling of manipulation of micro/nanoparticles on rough surfaces”, Journal Applied Surface Science, 2011, pp. 6503-6513.
- [10] Daeinabi, K., and Korayem, M. H., “Indentation analysis of nano-particle using nano-contact mechanics models during nano-manipulation based on atomic force microscopy”, J. Nanopart Res, Vol. 13, No. 3, 2010, pp. 1075-1091.
- [11] Tafazzoli, A., and Sitti, M., “Dynamic modes of nanoparticle motion during Nanoprobe Based Manipulation”, ASME Proc. of 4th IEEE Conf. on Nanotechnology, Munich, Germany, August 2004.
- [12] Fathi, Y. M., Ghorbel, H., and Dabney, J. B., “Nanomanipulation modeling and simulation”, Proceedings of ASME international mechanical engineering congress & exposition, November, Chicago, Illinois, USA; 2006.
- [13] Jalili, N., Dadfarnia, M., and Dawson, D. M., “A fresh insight into the microcantilever-Sample interaction problem in non-contact atomic force microscopy”, ASME J Dynamic Syst. Measur Control; Vol. 126, 2004, pp. 327-35.
- [14] Babahosseini, H., Mahboobi, S. H., and Meghdari, A., “Dynamic modeling and simulation of nanoparticle motion in AFM-based nanomanipulation using two nanoscale friction models”, Accepted for ASME/IMECE09, 2009.
- [15] Slotine, J. J., “Sliding controller design for nonlinear system”, International Journal of Control, Vol. 40, 1984, pp. 421-434.
- [16] Yang, Q., and Jagannathan, S., “Nanomanipulation using atomic force microscope with drift compensation”, In Proceedings of the American control conference, 2006, pp. 514-519.

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