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 todesign 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 Ydirection 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 demonstratedin 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 Fz, lateral force Fy and moment Mθ which are proportional to the deflection and the torsion of the microcantilever.

$$K_z = \frac{Ewt^3}{4L^3} \rightarrow \qquad F_z = K_z z_c \tag{1}$$

$$K_y = \frac{Ew^3t}{4L^3} \rightarrow \qquad F_y = K_y y_c \tag{2}$$

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

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].

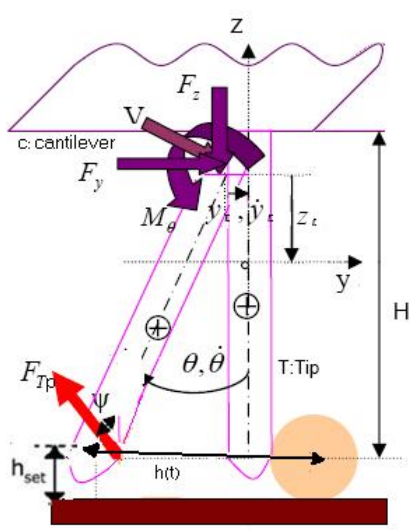

Fig. 1 Free body diagram of AFM lumped parameters model during nano-manipulation [1]

In Fig. 1, y_t and yc 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 θ 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 'θ' can be derived from governing equations on the AFM as:

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

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

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

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 ψ is the tip/particle angle. Moreover F_{tp}, Derjaguin interaction model, is functions of the separation distance of the tip/ particle h(t) and ψ, 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-particlein the *y* direction and the balancing equation in the z direction for the nano-particle can be written as follow:

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

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

$$A_{ps}^{adh}=\frac{H_{PS}R_P}{6a_0^2} \tag{9}$$

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.

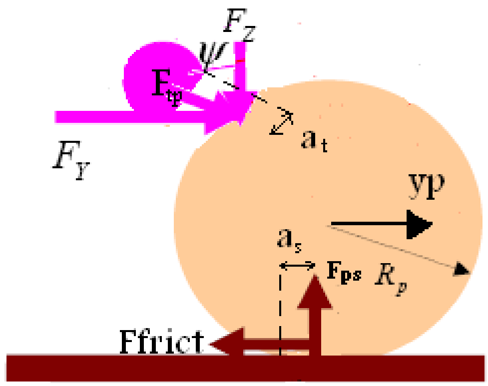

Fig. 2 Dynamic model of the nano-particle which experiences interaction forces and friction force during manipulation [1]

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:

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

In this work, the number of state variables are eight. They are *θ*, 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.

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

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

$$-(\frac{dy_5}{dt}\acute{H}\cos y_1 - \acute{H}\dot{y}_1{}^2 \sin y_1)(\frac{m_t+2m_c}{2}))$$

$$\frac{dy_7}{dt} = \ddot{y}_p = \frac{1}{m_p}(F_{tp}\sin\psi - \mathrm{sign}(\dot{y}_p)F_{frict})$$

$$\frac{dy_8}{dt} = \ddot{z}_t = \frac{1}{(m_t+m_c)}(-F_{tp}\cos\psi - k_z(z_t - \acute{H}\cos y_1)$$

$$-(\frac{m_t+2m_c}{2})(\frac{dy_5}{dt}\acute{H}\sin y_1 + \acute{H}\dot{y}_1{}^2\cos y_1) \quad (11)$$

The sliding surfaces of this system can be defined as:

$$e_1 = \theta - \theta_{set} \quad (12)$$

$$e_2 = y_t - y_{t.set} \quad (13)$$

$$s_1 = \dot{\theta} + \lambda_1 e_1 \quad (14)$$

$$s_2 = \dot{y}_t + \lambda_3 e_2 \quad (15)$$

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:

$$V = |s_1| + \lambda_2|s_2| \quad (16)$$

λ_2 is a positive variable defined real number between 0 and 1.

$$\dot{V} = sign(V) \quad (17)$$

The derivative of (17) is given by:

$$\dot{V} = \frac{s_1\dot{s_1}}{|s_1|} + \lambda_2\frac{s_2\dot{s_2}}{|s_2|} = \mathrm{sgn}(s_1)\dot{s_1} + \lambda_2\mathrm{sgn}(s_2)\dot{s_2} \quad (18)$$

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 ($\dot{V} = -\eta sat(V/\varphi)$) 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 θ and y_t track θ_{set} and $y_{t.set}$ respectively. Using the Lyapunov-based stability, the control signal U as a force input control is presented as follows:

$$U = \frac{-\eta\mathrm{sat}(V/\varphi) - (F_1(y)+\lambda_1 y_5)\mathrm{sgn}(s_1) - \lambda_2(F_2(y)+\lambda_3 y_6)\mathrm{sgn}(s_2)}{G_1(y)\mathrm{sgn}(s_1) + \lambda_2 G_2(y)\mathrm{sgn}(s_2)} \quad (19)$$

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

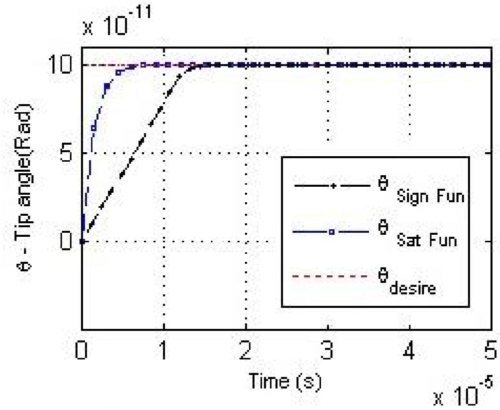

Fig. 3 The angle of AFM tip after control with SMC

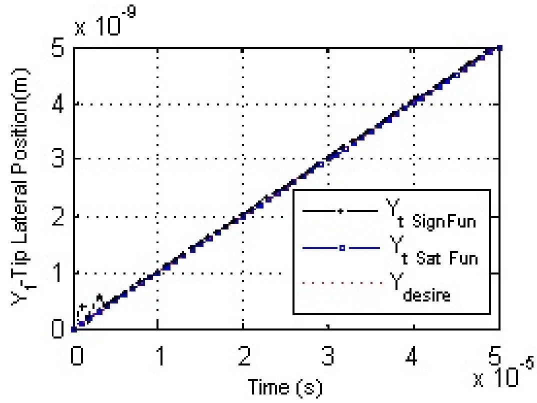

Fig. 4 The displacement of AFM tip during manipulation after control with SMC

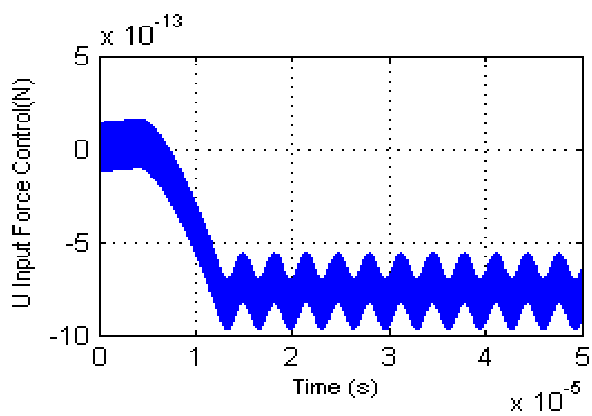

Fig. 5 The Input force control with sign function

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	φ	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, μ_{ps} is the particle-substrate sliding friction coefficient, F_{PS} denote the particle-substrate iteraction force and τ 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.

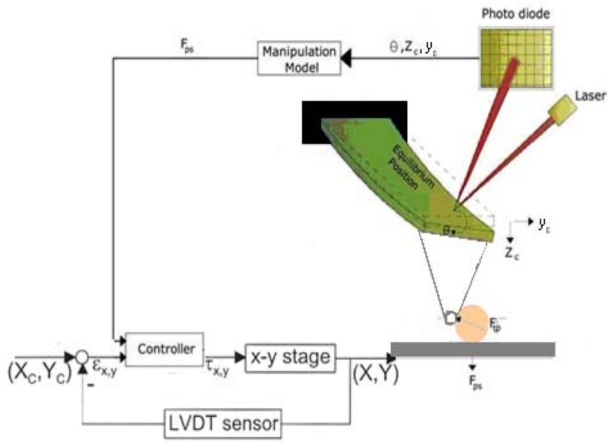

Fig. 6 Control scheme for positioning the cantilever tip during lateral nano-manipulation

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

$$\begin{bmatrix} s_x \\ s_y \end{bmatrix} = \dot{e}_s - \lambda e_s \quad (25)$$

$$\begin{bmatrix} \tau_x \\ \tau_y \end{bmatrix} = (\begin{bmatrix} -ksgn(s_x) \\ -ksgn(s_y) \end{bmatrix} - \lambda \begin{bmatrix} \dot{x}_s \\ \dot{y}_s \end{bmatrix} - \mathrm{F} - \mathrm{D})/\mathrm{G} \quad (26)$$

$[x_s y_s]^T$ 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 λ.

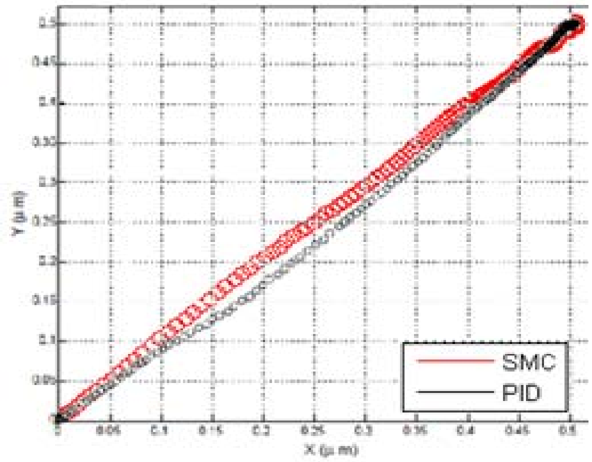

Fig. 7 Comparison control motion of nano-particle from the (0,0) point to (0.5μm,0.5μm) position during pushing to validate the presented sliding controller

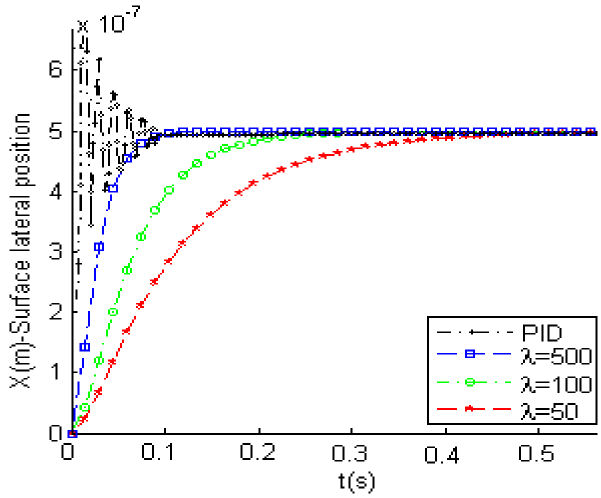

Fig. 8 Comparison step responses of the designed sliding mode controller and PID

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]:

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

Table 2 Values of the controller used in simulation

Parameter	Value	Parameter	Value
λ_1	50	φ	1e-10
λ_2	1e+2	k	2e-13
λ_3	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 λ increasing from 50 to 500, the settling time is shortened greatly. Thus, λ=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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