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Sensitivity analysis of nanoparticles pushing manipulation by AFM in a robust controlled process

E. Omidi, A.H. Korayem, M.H. Korayem*

Robotic Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

This paper investigates the sensitivity of nanoparticle parameters in a robust controlled process, by a compatible nanomanipulation model consisting of all effective phenomena in nanoscale. The dynamic model of nanoparticle displacement utilizes the Lund–Grenoble (LuGre) friction model, since it demonstrates pre-slip displacement, friction delay, various forces of failure and the stick-slip movement, with respect to other presented models. Also, the interaction force between nanoparticle and AFM cantilever tip are modeled by using the Derjaguin model. Sliding mode control (SMC) approach is used to provide the desired substrate motion trajectory, despite the challenges in the piezoelectric substrate motion control, consisting of thermal drift, hysteresis, and other uncertainties. In this paper, the dynamic model of nanoparticle manipulation is expressed to determine the nanoparticle behavior for substrate movement with desired trajectory and the effect of pre-process selections of the result of the manipulation. Depending on obtained diagrams for parameters sensitivity, the prediction of manipulation result is more precise, and also this is effective on choosing of proper initial condition and parameter selection in pushing purposes. Finally, it can be used to adjust proper pushing time and input for an accurate and successful pushing and assembly. It also provides a real-time visualization during micro/nanomanipulation and increases complexity of the resulting created structures.

1. Introduction

Nanomanipulation deals with the controlled manipulation of micro/nano-objects and it is the basic approach for building useful devices from nanoscale components such as atoms/molecules in top-down or bottom-up fabrication techniques [1]. In this way, some researchers have focused on modeling and its applications to motion analysis of nanoparticles or the probe tip [2–6]. The AFM probe consists of a cantilever and a tapered tip, and it is used as a manipulator. Manipulation of nanoparticles has been widespread of interest for last years, and dynamic modeling is a basic tool for understanding the pushing procedure at real time. The initial model for pushing was provided by Falvo et al., but in this model, the forces due to the scale changing were not considered [2]. The first model that considered the surface forces and contact deformations was proposed by Sitti and Hashimoto [3]. It used JKR theory of contact mechanics in which a discrete system model is used to design teleoperated control of pushing. Tafazzoli and Sitti presented a more satisfactory model for the nanoparticles' pushing process [4]. They tried to simulate a real-time nanomanipulation. Using this model, Korayem and Zakeri studied pushing of nanoparticles and developed the model to obtain the sensitivity of pushing critical force and critical time due to variations of geometrical and material parameters [5]. In later models, researchers have presented some different approaches to fulfill the prior deficiencies. Being more focused on the interaction forces between AFM probe, sample and tip displacement modeling, recent studies are in a better agreement with experimental results. Babahosseini et al. has solved the interaction force's problem, but the lack of exactness in cantilever modeling for more desirable trajectories of substrate displacement still remains [6]. Landolsi and Ghorbel provided a new modeling of tip displacement that is much more compatible with the dynamics of nanoparticle, and the results of this kind of modeling is more reliable [7].

On the other hand, since the AFMs were made for imaging with constant speed of substrate movement, there has been always a tendency to perform this process with such an approach from the early works [3,4]. However, the proficiency of manipulation using AFM requires a more flexible method which can undergo any desired controlled motion.

In this work, AFM probe and nanoparticle dynamics are modeled according to the most compatible and exact approaches and later,

* Corresponding author at: Robotic Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology, P.O. Box 13114-16846, Tehran, Iran. Tel.: +98 21 77240194.
E-mail address: hkorayem@iust.ac.ir (M.H. Korayem).

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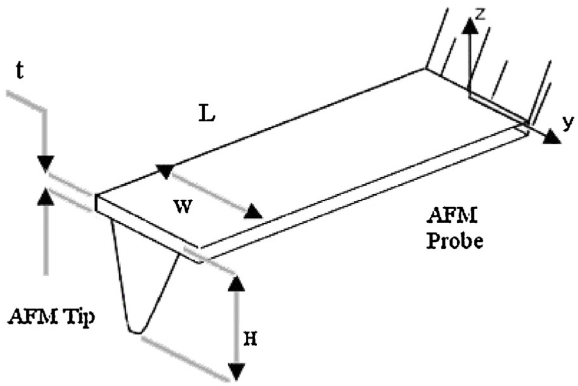

Fig. 1. AFM probe and its geometries [4].

interaction and friction forces are investigated and modeled. Then, the frequent used piezoelectric actuated stage model is expressed and a robust observer–base controller for displacement in nano scale is designed, using sliding mode control approach (SMC), considering all probable uncertainties and manipulation requirements. Then, the behavior of nanoparticle in this process, regarding to contact and friction forces is studied under the dynamic model of probe and particle. Dependency of friction force and other variables to the substrate velocity, nanoparticle size and material, cantilever types and control parameters are analyzed and compared.

2. Problem definition

Manipulation process in pushing phase using AFM generally consists of pushing the nanoparticle to the final desired location in a controlled process. The determination of AFM dynamics in pushing purposes requires modeling probe deformation [4]. The AFM, which is used as a manipulation tool for nanoparticle positioning, typically consists of a conical probe with a spherical tip, connected to a cantilever at the end (Fig. 1). The AFM geometrical parameters are *L*, *W*, *t*, *H*.

After a non-contact imaging scan of the surface, the location of desired nanoparticle to be displaced is exactly determined (Fig. 2, phase ‘a’). For the next step, probe tip is moved to the desired position which has an initial distance D_s from nanoparticle or in contact with it. The height H_s of the probe should be chosen that the probe will not slip over the particle (Fig. 2, phase ‘b’). After providing all the initial conditions, nanoparticle is pushed by the probe tip, due to the force exerted on it, by means of a relative motion between probe and nanoparticle, when the holder substrate of sample starts to move (Fig. 2, phase ‘c’). Providing all the satisfactory conditions such that the nanoparticle will not slip near or over the probe [5], nanoparticle is moved to the final desired location in this controlled process.

3. Manipulation modeling

3.1. Atomic force microscope probe

From the early works by Sitti and Hashimoto, manipulation was modeled by considering a cantilever beam connected to a base, and a rigid probe connected to its other side, contact dynamics were calculated using the exerted forces by probe to sample [3]. In later work by Tafazzoli and Sitti, cantilever beam assumption was followed by considering a constant speed manipulation; deformations of cantilever beam’s tip and consequently the probe tip were calculated using some geometrical calculations and assumptions [4]. However this model lacks exactness, especially in the results of experimental and calculated values of first natural frequency of the beam. Babahosseini et al. has used the same model for deformations and interaction forces are calculated according to this displacement model [6]. Recently, Landolsi and Ghorbel have used a dynamical model for FFM probe’s tip displacement, which can be used in the calculation of the interaction force between probe and sample and then, in sample displacement [7].

Dynamic modeling of the nano-tip module of nanomanipulation could be treated as a point mass interacting with the sample as lumped model. The assumption of a small deflection is implicit in the proposed lumped mass model. Cantilever beam and its

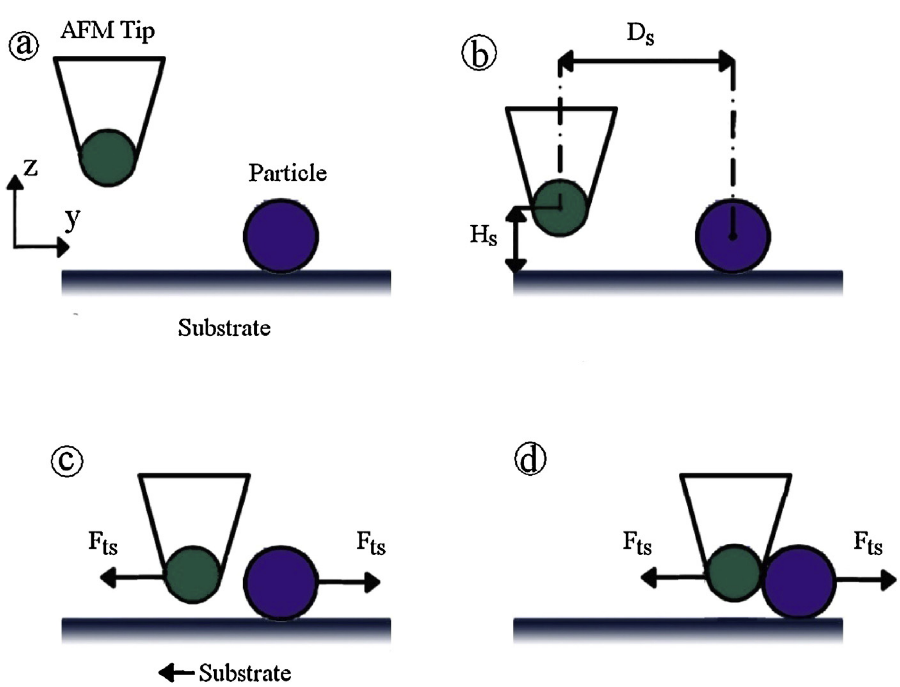

Fig. 2. Schematic view of manipulation steps.