Chapter 7
Virtual Tooling for Nanoassembly and Nanomanipulations

Zhidong Wang, Lianqing Liu, Jing Huo, Zhiyu Wang, Ning Xi, and Zaili Dong

Abstract  Atomic force microscopy (AFM) (Binning et al., Phys Rev Lett 56:930–933, 1986) has been used as a nanomanipulation tool recently because it not only has high resolution scanning ability but also can be controlled as an end-effector in the nanoenvironment (Junno et al., Appl Phys Lett 66:3627–3629, 1995). There are several challenging problems including controller design with relatively large thermal drift and other uncertainties, real-time positioning and manipulation control with sensor feedback, and nanosensing and manipulation planning. In the last decade, many researchers are working on these problems and some methods have been proposed that solved these problems partially (Chen et al., IEEE Trans Autom Sci Eng 3:208–217, 2006; Li et al., IEEE Trans Nanotechnol 4:605–614, 2005; Resch et al., Langmuir 14:6613–6616, 1998; Hansen et al., Nanotechnology 9:337–342, 1998; Sitti, IEEE ASME Trans Mechatron 9:343–348, 2004). However, the problem caused by single tip interaction is still hindering its efficiency especially in handling nanoparticles/nano-objects to form patterns or nanostructures.

Z. Wang
Department of Advanced Robotics, Chiba Institute of Technology, Tsudanuma 2-17-1, Narashino, Chiba, Japan
E-mail: zhidong.wang@it-chiba.ac.jp

L. Liu • Z. Wang • Z. Dong
State Key Laboratory of Robotics, Shenyang Institute of Automation, CAS, 114 Nanta Street, Shenhe District, Shenyang 110016, China
E-mail: lqliu@sia.cn; zywang@sia.cn; dzl@sia.cn

J. Huo
College of Information Science and Engineering, Northeastern University, Shenyang 110004, China
E-mail: bluerainhj@163.com

N. Xi
Department of Electrical and Computer Engineering, Michigan State University, 2120 Engineering Building, East Lansing, MI 48824-1226, USA
E-mail: xin@egr.msu.edu

Tools are usually designed and used for object handling or other tasks especially for having higher efficiency and accuracy or coping with various uncertainties on task performing. We proposed a concept of virtual nanohand which mimicking multi-fingered hand and controlling an AFM tip to form a virtual tool for achieving stable nano manipulation and nanoassembly. The nanohand strategy is implemented by moving the AFM tip to a set of predefined trajectories in relative high frequency. It allows us easily to design and apply various virtual tools for coping with requirements in nanomanipulation. This virtual tooling strategy is a solution with good potential on realizing high efficiency nanoassembly and nanomanipulation.

7.1 Background

It is well known that nanoparticle is an important nanomaterial and widely used for many research areas to study new phenomenon at nanoscale. With the nanoparticles, Maier et al. proved the diffusion effect of the electromagnetic energy transport [1]. Liu et al. studied the surface-enhanced Raman scattering phenomenon [2]. Makaliwe and Requicha developed an automatic path planning method for nanoparticle assembly [3]. Li et al. successfully demonstrated nanoparticles manipulation through the developed augmented reality system which can provide the real-time visual and force feedback [4]. Chen et al. developed a CAD-guided automatic nanoassembly system to handle nanoparticles and nanorods [5].

However, current commercial AFM only has one single sharp tip for nano-object manipulation. In the conventional manipulation process, the nano-object is imaged with the feedback engaged in the first. Then we need to turn off the feedback in $z$ direction and move the AFM tip to contact and push the nano-object. The contacting area between AFM tip and the nano-object is very small and, a nano-object is usually lost from contact with the AFM tip. Two reasons are mainly considered. One reason is that the AFM tip slips over the nano-object in case that resistance force from the object is relatively large during the manipulation. Another and major reason is that the nano-object may slip away from the AFM tip when the tip is not exactly pushing on the central point of the nano-object. When the object is lost, a new image scan is necessary for relocating the lost nano-object. In [6], an active probe control method is proposed to prevent the tip from slipping over the object. By actively control the rigidity of the cantilever, the cantilever becomes rigid during manipulation and a high-sensitive interaction force is calculated from the control signal. This method also can detect if the object is lost through the force feedback. But it is difficult to know the exact position of the lost object in this situation and a new scanning procedure is still necessary to find the missed object. A local scan method is proposed in [7] to relocate the missed particle in real time, but it is only a remedial method. If the particle is lost quite often, the time consumed by local scan may be a new bottleneck for high efficiency manipulation. Thus, the fundamental approach is that the nano-object can be real-time stably controlled by the AFM tip with losing during the whole process of nanomanipulation.
In this chapter, a nanohand strategy which mimics multi-tip object pushing is introduced to achieve stable nano-object handling with a single AFM tip. Kinematics and statics models of nanoparticles and nanorods pushed by an AFM tip are developed for estimating the possible location of the nano-object center in real time and for determining properties of the nanohand. Some simulation and experiment results are provided for illustrating the validity of the proposed nanohand strategy on performing stable and controllable nano-object manipulation.

7.2 Uncertainty in Nanomanipulation

As a basic nanomanipulation task, we focus on moving a nanoparticle from one place to another by using a single-tip AFM. The simple and effective strategy is pushing the particle center by the AFM tip. In this process, the AFM is used either as a manipulation tool or an imaging tool, but not both at the same time. As pushing a ball in macro world, the nanoparticle will rotate away from the direction of pushing in case that the end-effector is not exactly pushing on the particle center. This phenomenon is significant in performing a nanomanipulation/assembly task than macro world manipulation, because the uncertainty of AFM tip position from various reasons such as temperature drift, creep, etc, is relatively large comparing with the size of nano-objects. Additionally, the uncertainty of resistant force between the supporting surface and the target object cannot be ignorable and be another reason to make the particle deviate from the target direction even lost.

Figure 7.1 shows two results of nanoparticle pushing experiments which is under the same experiment setting. The nanoparticle $P_1$ is the target object. Other two particles in the upper part of scan images are used as references for canceling relative position error between two scan images. By overlapping images scanned before and after the pushing, movement of particle $P_1$ can be observed. In the two manipulation processes, the pushing point is set to the center of the particle and the pushing distance is 500nm. Both horizontal and vertical displacements of two experiments are different, because positioning error of the AFM tip exists. Furthermore, the AFM tip as an end-effector can only apply a point contacting force on the nano-object. Both of these reasons result a wide range area of possible positions of the particle center after manipulation (Fig. 7.2). In other words, the manipulation accuracy is poor especially when the pushing distance increases.

Nanorod is also a common nano-object used to construct nanostructures in nanomanipulation. When a rod is pushed by an AFM tip, both translational and rotational motion occurs during manipulation, and the rod rotates around an instantaneous center of rotation depending on the position of pushing contact point.

In Fig. 7.3, experimental results show that the instantaneous center of rotation is different under different pushing points. If the pushing point is choose inappropriately, the rod can easily slip away from the tip and the manipulation would fail. Usually, a user can only have the result of manipulation after taking the second scan image. This lets manipulation of nanorods over long distances be very
Fig. 7.1 The pushing experiment results under the same initial conditions. The particle \( P_1 \) is pushed 500nm horizontally by AFM tip. The first experiment: (a) Initial position (b) Resultant position (c) Overlapping image of (a) and (b) for showing particle’s movement. The second experiment: (d) Initial position (e) Resultant position (f) Overlapping image of (d) and (e). It is clear that the results are different in the horizontal and vertical displacements both.

Fig. 7.2 A nanoparticle may be pushed from initial position \( A \) to a wide range area \( B \) because of AFM tip position error.

time-consuming. In addition, the contact between the AFM tip and the nano-object is too small to realize posture control during manipulation. Tip position error makes the manipulation unstable and uncontrollable. Figure 7.4 shows the possible positions after the nanorod is pushed by the single AFM tip. Range of possible positions of the rod is a relative wide area, and the posture will be different with the initial in general. Then, stable pushing strategy is important for efficient nanomanipulation.
Fig. 7.3 The experimental results that the instantaneous center of rotation is (a) inside the rod, (b) at the end of the rod and (c) out of the rod while the nanorod is pushed on different contacting point by AFM tip.

Fig. 7.4 The rod is pushed to a wide range area around the target position and posture because of the inaccuracy of the AFM tip position.

7.3 Nanohand Strategy for Stable Manipulation and Assembly

In multi-robot object transportation, concepts of object closure [8] and conditional closure are proposed to solve the problem of position error of mobile robots during manipulation. Based on the concept of conditional closure, we proposed a nano-object transportation strategy: a strategy to mimic multi-fingered hand with single AFM tip [9, 10]. We name it virtual nanohand. The nanohand strategy is implemented by moving the AFM tip to a set of predefined positions and generating...
a short pushing action to the target object from those positions in relative high frequency. It can achieve the effect of multi-tip manipulation for stable pushing only with a single AFM tip. By incorporating this strategy, the problem of pushing position error with a single end-effector can be resolved.

The concept of the nanohand based manipulation is shown in Fig. 7.5. The AFM tip is moved to a set of predefined positions with coverage shape Fig. 7.5(a), and pushes the particle in each position a small step sequentially. By repeating this kind of multiple pushing on two sides of the particle center in proper length of pushing step, the particle can be controlled within the nanohand while it is pushed. By modeling of the nanoparticle pushing by a single AFM tip and analyzing maximum errors of the pushing, the pushing points, pushing step-length and pushing speed of the nanohand can be designed for limiting the possible positions of particle center within an up-bonded range. Then, the nanoparticle can be controlled in real time by a single AFM tip without losing during manipulation.

Figure 7.5(b) shows the manipulation process using nanohand strategy to push a nanorod. By planning and controlling trajectory of the nanohand set, the rod can be moved forward in predefined distance first and then be rotated to its target posture even with certain position errors of the AFM tip. By using the nanohand strategy,

![Fig. 7.5](image.png)

**Fig. 7.5** By using nanohand strategy, the nanorod can be handled to the target position and orientation stably with upper-bounded error, even the error of the AFM tip cannot be ignored in nanomanipulation. (a) The particle can be pushed to a small and up-bounded area B by using nanohand strategy. (b) The effect of errors of AFM tip position can be reduced and stable pushing is realized by using nanohand strategy.
real-time position and posture control can be achieved as manipulation performed by multiple AFM tips.

### 7.4 Models of Nano-object Manipulation

The nanohand strategy imitates multi-tip manipulation by planning pushing point set and pushing step-length. In determining these two parameters, kinematics and statics model of the nano-object in the manipulation are used. In discussing properties of mesoscopic objects, friction is no longer proportional to the normal load [11] and the acceleration is not the decisive factor which affects the movement of nano-object. On the other hand, in nanoscale, all the objects and substrates are covered by water. Viscous friction must be considered in modeling motion of nano-objects. Experiment results also show that different pushing velocities have different PSD voltage deflections while a nanoparticle or nanorod is pushed by using an AFM tip. Figure 7.6 shows the results that under the same pushing conditions, the PSD voltages change in lateral direction when the AFM tip pushes a nanorod with different velocities. The viscous friction effect is significant comparing with object manipulation in macro environments.

When the tip of AFM pushes the nanoparticle in contact mode, the force would make the particle deformed. Then a contact area will be formed between the substrate and the nanoparticle, and it could be modeled as a circular area with radius $R$ (Fig. 7.7). The radius of the contacting area can be calculated by using the Johnson–Kendall–Roberts (JKR) model [12, 13]. Assuming, the tip contacts the particle all the time during the manipulation, the pushing velocity is a constant, and the substrate is flat. Owing to adopt contact mode, the pushing force acting surface would be the plane which is parallel to the substrate where contact area is on. So the particle can be simplified as a disk. It means that the contact area

![Fig. 7.6 Lateral PSD signal with different pushing velocities on pushing a nanorod](image-url)
center’s movement can reflect the particle center’s movement, and then we can discuss the motion of the particle in 2D model (Fig. 7.7). Figure 7.7a is the side view that indicates the relationship of the forces. Figure 7.7b is the top view that indicates the relationship between the contact plane and the pushing plane. When a constant velocity is applied to a nanoparticle, the nanoparticle starts to rotate around an instantaneous center of rotation. If the substrate is a homogeneous media, the movement of the disk can be regarded as uniform circular motion.

$f_{PT}$ is the pushing force applied to the nanoparticle from the AFM tip, $f_{T}$ is the friction between the tip and the particle. $F_N$ is the particle–substrate normal forces in contact area. $f_r$ is the resistance force including particle–substrate friction and surface effect force. Because the surface of the substrate is covered with water, the viscous friction must be considered in $f_r$. Additionally, vertical components of the contacting forces ($f_{PT}$ and $f_{T}$) applied from the tip could be considered becoming large while pushing velocity increases. This will also lead the resistance friction and we also can model it as part of viscous friction. $R_P$ is the radius of the pushing plane, and it can be calculated according to the shape of the tip and diameter of the particle. $R$ is the equivalent radius of particle–surface interface. $\omega$ is the angular velocity of the rotation of the nanoparticle.

Experimental results have shown that the nanorod under pushing may have different kinds of behavior, which depends on its own geometry property. The aspect ratio of a nanorod is defined as $\sigma = L / d$, where $L$ is the length of the rod and $d$ is the width. As mentioned in [14], a rod with aspect ratio of $\sigma < 15$ could be considered as rigid one and its rotation behavior can be observed. This conclusion is also verified in our experiments shown as in Fig. 7.3. It is easy to prove that the instantaneous center of rotation of the nanorod must be on the axis of the rod. Then as shown in Fig. 7.8, the rod can be simplified as a rigid line segment and motion of manipulated rod can be modeled as nanoparticle manipulation. Accordingly, that the rotation of the rod is the uniform circular motion can be assumed.
Considering the effect of pushing speed on the friction between the nano-object and the flat substrate, the distributed friction force \( f_r \) of small element on object’s support area consists of two components, coulomb friction and viscous friction:

\[
\begin{align*}
    f_r &= f_c + f_v \\
    f_c &= \mu N_r \\
    f_v &= cv_r = cr\omega
\end{align*}
\]  

(7.1)  

(7.2)  

(7.3)

where, \( f_c \) is the dynamic coulomb friction force at a small element and is a constant. \( \mu \) is the coefficient of dynamic friction, and \( N_r \) is the pressure of the element on the normal direction of the substrate. \( f_v \) is the viscous friction force, \( c \) is the viscous friction coefficient, and \( v_r \) is the velocity of the element. \( r \) is the length from contacting point of the AFM tip to the instant center of rotation of the nano-object. \( \omega \) is the angular velocity of the object pushed and is the function of both the velocity at pushing point \( P \) and the position of the instant center of rotation.

### 7.5 Kinematics and Statics of Nano-object Pushing

Different from object handling in the macro world, the effect of mass on motion can be ignored in nanoscale, and only balance of the static forces applied on the object should be considered. We discuss the static model of a nanorod first, because supporting area of a nanoparticle can be modeled as set of multiple line elements which are with the same kinematic and static properties of nanorods.

The external forces applied on the rod in the substrate surface plane can be modeled as shown in Figs. 7.9 and 7.10 for representing cases that the instant center of rotation \( I_{RC} \) is at outside the rod and inside the rod respectively. \( L \) denotes the
Fig. 7.9 The static model while the instantaneous center of rotation is at the outside of the rod when the contacting point is near the center of the rod.

Fig. 7.10 The static model of nanorod while the instantaneous center of rotation is at the inside the rod when the contacting point is far from the rod center.

The length of the rod, $l$ denotes the distance between the pushing point and the reference end $A$, $s$ denotes the distance between the instantaneous center of rotation and the reference end, $r$ denotes the distance between a small element of the rod and the reference end $A$, $f_r$ is the distributed friction force on the small element, and $F$ is the pushing force from the tip. We assume that the rod is pushed in perpendicular to the rod and there is no motion in the direction of the rod.

When the pushing point is near the center of the nanorod, the instantaneous center of rotation maybe outside the rod (Fig. 7.9). The angular velocity of the rod is with the following relation to pushing velocity.

$$\omega = \frac{v_p}{l + s}$$

where, $v_p$ is the velocity of the pushing point. All torques around $I_{RC}$ are self-balanced during manipulation. The static equation can be written as:
where, left side of the equation denotes the moment applied by the AFM tip, and right side represents the friction resistance consisting of dynamic coulomb friction and viscous friction force which are calculated by integrating friction forces applied on small elements of the rod.

Figure 7.10 shows the model that the instantaneous center of rotation is inside the rod when the pushing point is relatively far from the center of the nanorod.

In this case, the angular velocity of rotation is expressed as following equation:

\[ \omega = \frac{v_p}{l - s} \]  

(7.6)

All the torques around \( I_{RC} \) are self-balanced during smooth movement, so we can get following expression:

\[
F(l - s) = \int_0^{L-s} (f_c + f_v) \cdot r \, dr + \int_0^{s} (f_c + f_v) \cdot r \, dr
\]

\[
= \frac{1}{2} f_c (L - s)^2 + \frac{1}{2} f_c s^2 + \int_0^{L-s} c_\omega \cdot r^2 \, d + \int_0^{s} c_\omega \cdot r^2 \, dr
\]

\[
= \frac{1}{2} f_c (L - s)^2 + \frac{1}{2} f_c s^2 + \frac{v_p}{l - s} \frac{1}{3} \left[ (L - s)^3 + s^3 \right]
\]

(7.7)

There must be an \( s \) which can minimize \( F \), in which the rod begins to rotate once the pushing force \( F \) reaches this minimum force \( F_{\text{min}} \). Therefore, the static point \( I_{RC} \) can be determined by following equation with (7.5) and (7.7).

\[
\frac{dF}{ds} = 0
\]

(7.8)

When the instant center of rotation at each moment is derived, motion of the nanorod can be obtained numerically while initial conditions are given. Then under a certain pushing velocity and a certain pushing angle, the instantaneous center of the nanorod can be calculated and the pushing points can be determined based on that result to form the virtual nanohand.

Similar with nanorod pushing, the statics model of nanoparticle pushing can be derived by integrating friction resistance on all elements of the support area.
Since both translational and rotational motion in general, velocities of elements are different from each other.

For convenience of study, we represent the contact area by a series of straight lines passing through the instant center of rotation, as shown in Fig. 7.11. For each line, distributed friction can be modeled as the model of a nanorod. \( V_r \) is the velocity of element \( r \) and is given by \( V_r = r \omega \), where \( \omega \) is the angular velocity and is invariant, \( r \) is the distance between the small element and the instant center of rotation \( I_{RC} \). Additionally, we have the following condition for \( \omega \):

\[
\omega = \frac{V_p}{L_p} \tag{7.9}
\]

where, \( V_p \) denotes the pushing velocity of the AFM tip, and \( L_p \) is the distance from the pushing point \( P \) to the instant center of rotation \( I_{RC} \). Here, we only discuss case that \( I_{RC} \) is located outside of the support area since the main purpose on handling a nanoparticle is moving it to a target position.

The friction and the torque exerted on the line element are derived by the following equations (Fig. 7.12(a)):

\[
f_\theta = \int_{S_\theta - \frac{L}{2}}^{S_\theta + \frac{L}{2}} f_r \, dr \tag{7.10}
\]

\[
M_\theta = \int_{S_\theta - \frac{L}{2}}^{S_\theta + \frac{L}{2}} f_r \cdot r \, dr \tag{7.11}
\]

where \( S_\theta \) denotes the distance from the center of the straight line to the instant center of rotation, \( L \) is the length of the straight line. \( S_\theta \) and \( L \) in Fig. 7.12(a) can be written

\[
S_\theta = S \cdot \sin \theta \tag{7.12}
\]
Fig. 7.12  (a) The equivalent resistance force and moment on the line segment (b) The equivalent resistance forces from two symmetric line segments

\[ L = 2 \cdot \sqrt{R^2 - (S \cdot \cos \theta)^2} \]  
(7.13)

with \( S \) is the distance from the center of the contact area \( O \) to the instant center of rotation \( I_{RC} \), \( R \) is the radius of the contact area, \( \theta \) is the angle between \( x_0 \) axis and the straight line, and the range is \( 0 < \theta \leq \frac{\pi}{2} + \arcsin \frac{R}{S} \).

Then \( f_\theta \) can be resolved into \( f_{\theta x_0} \) and \( f_{\theta y_0} \).

\[ f_{\theta x_0} = f_\theta \cdot \sin \theta \]  
(7.14)

\[ f_{\theta y_0} = f_\theta \cdot \cos \theta \]  
(7.15)

Because the straight line elements are symmetrical about the coordinate axis, the vertical component \( f_{\theta y_0} \) can be cancelation. Then the friction force \( f_{fr} \) and the friction torque \( M \) which exert on the nanoparticle can be obtained.

\[ f_{fr} = \int_{\frac{\pi}{2} - \arcsin \frac{R}{S}}^{\frac{\pi}{2} + \arcsin \frac{R}{S}} f_\theta \cdot \sin \theta \cdot d\theta \]  
(7.16)

\[ M = \int_{\frac{\pi}{2} - \arcsin \frac{R}{S}}^{\frac{\pi}{2} + \arcsin \frac{R}{S}} M_\theta \cdot d\theta \]  
(7.17)
For the nanoparticle the forces and the torques are both balanced, so we can get following expressions

\[ M_P = M \]  \hspace{1cm} (7.18)

\[ f_P = f_{IR} \]  \hspace{1cm} (7.19)

where \( f_P \) is the component of pushing force and \( M_P \) is the torque of it. In order to be convenient to analyze and solve problems, transformation of coordinates is done, shown as in Fig. 7.13. \( \theta_0 \) is the angle of the transformation and can be determined from the equation

\[ S \cdot \sin \theta_0 = R_P \cdot \cos(\pi - \theta_P) = -R_P \cdot \cos \theta_P \]  \hspace{1cm} (7.20)

where \( \theta_P \) is the angle between the pushing point and the center. According to the balance relationship between the force \( f_P \) and the torque \( M_P \), the equation can be obtained

\[ f_P \cdot L_P \cdot \cos \theta_0 = M_P \]  \hspace{1cm} (7.21)

where, \( L_P = S \cdot \cos \theta_0 + R_P \cdot \sin \theta_P \).
From (7.16) to (7.21), we can get the following equation.

\[
\int_{\frac{\pi}{2} + \arcsin \frac{R}{EM}}^{\frac{\pi}{2} - \arcsin \frac{R}{EM}} (f_\theta \cdot \sin \theta \cdot L_P \cdot \cos \theta_0 - M_\theta) \cdot d\theta = 0
\]  

(7.22)

Ultimately, by solving integral and setup parameters, (7.18) can be written as an expression of \( S \). Using means of numerical integration, we can get the \( S \) which is the distance from the center of the contact area to the instant center of rotation.

According to the characteristic of rigid body motion, we can get the following constraint condition:

\[
\frac{V_P}{L_P} = \frac{V_O}{S}
\]

(7.23)

where \( V_O \) is the velocity of the particle center.

Then under a certain pushing velocity and a certain pushing angle, the deflection of the center can be calculated and the pushing points can be determined based on that result. During the manipulation, according to the location of the center change the pushing points and the pushing step-length to form the nanohand, then the nanoparticle is real-time controllable. Applying the nanohand strategy would resolve the problems of nanoparticle losing and inefficient positioning.

### 7.6 Experiments and Numerical Analysis

#### 7.6.1 Nanoparticle Pushing Experiments and Numerical Analysis

In this simulation, a radius of 100nm nanoparticle is manipulated on the CD substrate. The experimental tip is NSC15/AIBS which is product by MikroMasch. For getting variable \( S \) in the statics model of nanoparticle, the constant parameters \( f_c \) and \( c \) must be determined. First, measuring the deflection sensitivity \( \gamma \) of the AFM tip by means of force curve by experiments, we have \( \gamma = 60\text{nm/V} \). Second, using the same pushing angle and the same pushing step-length, push the nanoparticle five times with a certain velocity, record the PSD voltage deflection \( \delta_v \), and calculate the average value. The process is repeated six times with six different velocities. The spring coefficient of the AFM cantilever is relevant with the characteristic of AFM, it is a constant, here the coefficient \( k = 40\text{N/m} \). Assume that the contact angle of the tip and the particle isn’t changed when the tip pushes the particle, so based on the formulas \( x = \delta_v \times \gamma \) and \( f = kx \), the pushing force exerted on the nanoparticle can be calculated. Figure 7.14 shows the relationship between the pushing velocity and the force, the line shown in this figure is fitted by the method of least squares. The Y-intercept is the parameters \( f_c \) and the slope is the viscous friction coefficient \( c \).
With these calibrated parameters, we can obtain the distance $S$ between the particle center and the instant center of rotation by using numerical integration in Matlab, and then the velocity of the particle center can be calculated. In the nanoscale, contact deformations must be considered. Figure 7.15 shows the simulation results of the velocity of the particle center in different pushing angle. Under the same pushing velocity of the AFM tip, the velocity of the particle center will increase for all pushing angle while the equivalent radius of particle–surface interface increases.

When a nanoparticle is pushed by AFM tip, and the initial pushing angle $\theta_p = 13\pi / 12$, pushing velocity $V_p = 0.5 \mu m / s$, the equivalent radius of the AFM tip $R_T = 40$ nm, the pushing length is $500$ nm, then the experiment result is shown in Fig. 7.16. From Fig. 7.16(c), we can calculate that the horizontal displacement of the nanoparticle is about $422$ nm and the vertical deflection is about $71$ nm.

The simulation is done with the conditions of the Fig. 7.16 experiment. It is assumed that the pushing angle $\theta_p$ and the instant center of rotation $I_{RC}$ are invariable in the condition of $<100$ nm pushing length. The velocity and the location of the particle center pushed are calculated, and the trajectory of the particle center is estimated as shown in Fig. 7.17 based on calculated particle motion. In Fig. 7.17, the big cross dots are the start and target position of the nanoparticle center in the experiment. The dash line is the simulation curve and the final position of the simulation is with about $1$ nm errors. This simulation result illustrates the validity of the static model proposed, and the accuracy may increase when parameters are calibrated precisely and calculation step is set shorter in the simulation.
7.6.2 Nanorod Pushing Experiments and Numerical Analysis

Several experiments have been done for verifying the validity of the static model of nanorod manipulation. In the experiments, a ZnO nanorod is used as the target object. Figure 7.18 shows three experimental results. In these experimental processes, the nanorod is pushed by AFM tip under the same conditions, including that the initial pushing direction is perpendicular to the rod, the pushing velocity is 2.0 μm/s, the pushing length is about 1 μm, and the parameters of the rod are $L = 5.686 \mu m$ and $l = 4.186 \mu m$. In these three experiments, the initial posture of the rod is different. But the mica surface is flat, and we can assume that surface friction is the same in the all directions of the 2D coordinates. In another word, the initial pushing angle does not affect the manipulation results if the pushing direction is perpendicular to the rod.

Figure 7.18(a–c) are the overlapping scanning images generated from initial and resultant scanning. Figure 7.18(d–f) shows the same overlapping images but the initial position and posture of the rod is set in the $x$ direction, by rotating the images. Even the rod is pushed at the same point in the manipulation planning procedure,
The results of pushing are with some difference. Table 7.1 shows the displacements of the center point of the rod after three pushing experiments. $\Delta x$ is the horizontal displacement of the rod center, $\Delta y$ is the vertical displacement of the rod center, and the angle $\Delta \theta$ is the rotation angle of the rod.

From Table 7.1, we can confirm that even under the condition that all the pushing parameters and experimental circumstances the same, the manipulation results were different by each operation. We consider that the main reason for these is that position error of the AFM tip contacting with the rod causes the difference of rod’s motion. By using the static model of the nanorod mentioned above, the motion of the rod can be calculated not only for the planned contacting point of the AFM tip but also for the position contacting point including the error. Then this kind of numerical calculation will be essential tool to design the nanohand structure. Here the numerical calculations for the above-mentioned experiments are included for illustrating the validity of the proposed mode. We implement the static model of rod in the Matlab program. It is assumed that changes of the pushing angle and the instantaneous center of rotation can be ignored in a small pushing step. In the following calculation, the whole pushing action is divided into eight parts, where the motion of rod is generated in every 125nm each calculation step. Then the location of the instantaneous center of rotation is calculated, and the displacement of the rod
Fig. 7.19 Numerical simulation results with and without thinking about the position error of the AFM tip. In these figures, the crosses show the experimental result, the solid line with dots are the numerical simulation results not considering the position error of AFM tip and the dash line with dots are the simulation results considering the error. (a) Center displacement in $X$ direction in Exp. 1, Exp. 2 and Exp. 3. (b) Center displacement in $Y$ direction in Exp. 1, Exp. 2 and Exp. 3. (c) Change of rotation angle in Exp. 1, Exp. 2 and Exp. 3.

From the numerical simulation and experimental results, we can conclude that though the experimental conditions are the same, the results may be different with each other. Solid lines in Fig. 7.19 show the displacement of the center in both $X$, $Y$ direction and orientation angle of the rod. Also by considering position errors, the numerical simulation results will be improved. The dash lines in Fig. 7.19 are calculation results by adding some errors to planned contacting position, and show more near to the experiment result comparing with the blue ones which is calculated from planned contacting position only. In three simulation experiments, for getting better results, the value of the position error is different. For Exp. 1 the value is $-18\text{nm}$ that is the pushing point moved $18\text{nm}$ near to the pivot direction, in Exp. 2 the value is $16\text{nm}$ that is the pushing point moved $16\text{nm}$ far away from the pivot.
direction, in Exp. 3 the value is 46nm. From the numerical simulation results we can conclude that the position error must be one of the factors which are considered in process of modeling.

7.7 Conclusion

Almost all the existing AFM only has one single tip as the end effector, thus during nanoparticle manipulation, the interaction force between the nanoparticle and the tip can but be applied through a single point, which often leads the AFM tip to slip-away from the particle or split the particle due to their small contact area. This is one of the main bottlenecks for AFM-based high efficiency nanoparticle manipulation. To solve this problem, we proposed a nanohand strategy. Based on the self-balance conditions of the forces and the torques, the kinematics model of nanoparticle is developed, and the location of the center can be predicted at the each moment of manipulation, according to which the pushing points, pushing step-length and pushing speed can be planned artfully to form, a virtual nanohand. In this way, the manipulation effect as multi-tip does can be achieved with a single AFM tip. The simulation shows a stable and controllable nanoparticle pushing can be obtained. This method gives a feasible solution to compensate the shortcomings of single-tip based nanomanipulation and nanoassembly.

References


