Drift Compensation and Faulty Display Correction in Robotic Nano Manipulation

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Random drift and faulty visual display are the main problems in Atomic Force Microscopy (AFM) based robotic nanomanipulation. As far as we know, there are no effective methods available to solve these problems. In this paper, an On-line Sensing and Display (OSD) method is proposed to solve these problems. The OSD method mainly includes two subprocesses: Local-Scan-Before-Manipulation (LSBM) and Local-Scan-After-Manipulation (LSAM). During manipulation, LSBM and LSAM are on-line performed for random drift compensation and faulty visual display correction respectively. Through this way, the bad influence aroused from random drift and faulty visual display can be eliminated in real time. The visual feedback keeps consistent with the true environment changes during the process of manipulation, which makes several operations being finished without an image scan in between. Experiments show the increased effectiveness and efficiency of AFM based nanomanipulation.

Keywords: Nanomanipulation, Random Drift, Visual Display, Local Scan, AFM.

1. INTRODUCTION

Atomic Force Microscopy (AFM)\textsuperscript{1} has been used as a nanomanipulation tool for many years taking advantages of its high-resolution and high alignment accuracy.\textsuperscript{2,\textendash}\textsuperscript{6} As AFM is originally developed for imaging and characterization of surface, there are challenging problems when using it for nanomanipulation. Although these challenges have been solved to a certain extent after more than a decade’s efforts by researchers worldwide, we are still afflicted with the positioning errors aroused from random drift and the lack of highly reliable visual feedback.

Random drift, caused by the contraction and expansion of the mechanical system due to temperature, humidity changes,\textsuperscript{7,\textendash}\textsuperscript{9} leads to a position error between the current manipulation coordinate and the true environment, which makes it extremely hard to locate the probe and the objects accurately. For example, if the random drift is larger than the size of the nano-object, the AFM tip may not be able to touch the object at all during manipulation. Some research work has been carried out to handle these problems by estimation and compensation.\textsuperscript{9,\textendash}\textsuperscript{10} But all these methods are model based compensation, whether the compensation is successful or not lies on the degree of the model’s accuracy. In our experience, it is not easy and also takes time to obtain the accurate model parameters.

Faulty visual display is due to its generation mechanism. Actually up to date, there is no truly real-time feedback in AFM based nanomanipulation due to the slow speed of AFM scan. Nearly all the visual displays provided by current technologies are not the actual manipulation results but calculated from the behavioral models.\textsuperscript{11,\textendash}\textsuperscript{13} Due to the complexities and uncertainties in the nanoworld such as surface tension, van der Waals force, capillary force, it is difficult to accurately describe the objects’ behaviors with models. Thus, the modeling error often leads to a mismatch between the actual location of the objects and the displayed locations. As a result, the faulty visual display leads to a failed manipulation. A new image scan is repeatedly needed to correct the display errors, which dramatically decreases the efficiency and effectiveness of AFM based nanomanipulation.

From above discussion we can see, the problems caused by random drift and faulty visual display still stand as a grand challenge hindering the effectiveness of AFM based nanomanipulation. In this paper, based on our formerly developed augmented reality system,\textsuperscript{13} an On-line Sensing and Display (OSD) method is proposed to solve these problems. By combining OSD method with the augmented reality system, the reality of the visual display is greatly improved. The experimental results of using the

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augmented reality enhanced AFM system with OSD for manipulating nano-particles show that not only can random drift be effectively detected and compensated, but the mismatch between the visual display and the true environment can be on-line corrected after each step of manipulation without interrupting the manipulation, which lead to an increased efficiency and effectiveness of AFM based nanomanipulation.

2. ON-LINE SENSING AND DISPLAY

The OSD method includes two subprocess: Local-Scan-Before-Manipulation (LSBM) and Local-Scan-After-Manipulation (LSAM). LSBM is performed for eliminating the position error aroused from the random drift. LSAM is applied to correct the fault visual display caused by the modeling errors. To make our point more clear, an example of manipulating nano-particle is used to further explain this method. But this method does not limited to particles, it can be expanded to object’s with other shapes through minor modification.

2.1. LSBM Based Drift Compensation

In the AFM based nanomanipulation, finishing a manipulation task often includes three steps: identifying objects, manipulation and verifying the manipulation result with a new AFM image scan. During the process of identifying objects, the objects on the previous captured AFM image are identified and their positions are labeled. But due to the random drift, there will be a position error between the visual display coordinate and the true environment, thus the labeled positions may not represent the actual positions, which should be compensated prior to manipulation start.

Figure 1 shows the mechanism of detecting position error aroused from random drift during nano-particle manipulation. The solid circle $O$ represents the particle position on the AFM image before manipulation. Since there is a random drift, the particle is actually at the position of the dashed circle $O^*$, LSBM is performed to locate its real positions and compensates the position aroused from random drift.

The location of a nano-particle can be determined by its center position and radius. Since the radius of the nano-particle has been obtained in the process of identifying objects before the manipulation, the local scan only needs to relocate the actual center of the nano-particle. To get the actual center position of the particle, the local scan needs to scan at least two lines, one or more horizontal lines and one vertical line. First, as shown in Figure 1, AFM scans along Line $L_0$, which passes through point $O$, the displayed center of the particle on the image. If the particle was not found, then the scanning line moves up and down alternatively by a distance of $3R/2$ until the particle is found, where $R$ is the radius of particle. Once the particle is found, the scanning line forms two intersection points with the boundary of the particle, $P_1$ and $P_2$. A vertical line $V$, which goes through the midpoint between $P_1$ and $P_2$ and is perpendicular to the previous scanning line, is scanned to find the center of the particle. The vertical scanning line has two intersection points with the boundary of the particle, $Q_1$ and $Q_2$. The center of the nano-particle $O^*$ is located at the midpoint between $Q_1$ and $Q_2$. The length of the scanning line $L$ is determined by the maximum random drift distance such that $L > 2R + r_{max}$, where $r_{max}$ is the maximum random drift distance and is determined through experiments.

After the actual position is obtained, the random drift can be easily calculated through the difference between the displayed center position and the actual center position, such as:

$$
\begin{align*}
&\begin{cases}
    d_x = O_*^x - O_x \\
    d_y = O_*^y - O_y
  \end{cases}
\end{align*}
$$

(1)

Where $d_x$ and $d_y$ delegate the random drift values in $X$ and $Y$ direction respectively, $O_*^x$ delegates the actual position of the object center obtained through local scan, $O$ represents the initial labeled position in the previous captured AFM image. Many experimental observations indicate that the drift is essentially a translation (no rotation is involved), thus the position error calculated from the LSBM existed between each object in the image and the AFM tip with the same value. Therefore instead of updating the visual display image with the actual position of the single object, the random drift was compensated by multiplying the motion commands of the AFM tip with a transform matrix, such as:

$$
\begin{align*}
\begin{pmatrix}
P'_x \\
P'_y
\end{pmatrix} &= \begin{pmatrix}
1 & 0 & d_x \\
0 & 1 & d_y \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
P_x \\
P_y
\end{pmatrix}
\end{align*}
$$

(2)

Where $P_x$ and $P_y$ are the position command generated in the initial display coordinate. $P'_x$ and $P'_y$ are the true.
position command sent to the AFM tip after the random drift compensation. By intermittently executing this process before each step of manipulation, the position error caused by the random drift can be effectively eliminated.

2.2. LSAM Based Faulty Display Correction

Although a movie-like visual feedback is provided under the assistance of the augmented reality system during the process of manipulation, this kind of visual feedback is not the actual manipulation results but calculated from the behavioral models. Since any model may have errors comparing with the real environments, the visual feedback may not be consistent with the true manipulation result. Then a LSAM process is needed to correct the visual display error after each step of manipulation.

As shown in Figure 2, after manipulating the particle along the pushing direction, the solid circle $O'$ represents the model calculated location of the particle after manipulation. Since there may be some difference between the real location and the calculated location from the model, a LSAM is needed to correct the position errors in the visual display. First, AFM scans along line $L_0$, which passes through the initial actual center and along the tip motion direction. If the particle was not found, then the scanning line moves up and down along the direction perpendicular to Line $L_0$ alternatively by a distance of $3R/2$ until the particle is found. Once the particle is found, the scanning line forms two intersection points with the boundary of the particle, $P_1'$ and $P_2'$. Another line $V'$, which goes through the midpoint between $P_1'$ and $P_2'$ and is perpendicular to the previous scanning line, is scanned to find the actual center of the particle. The last scan line has two intersection points with the boundary of the particle, $Q_1'$ and $Q_2'$. The final actual center of the nano-particle $O''$, is located at the midpoint between $Q_1'$ and $Q_2'$. The length of the scanning line $L'$ is determined by the maximum random drift and the pushing distance such that $L' > \Delta + 2(R + r_{max})$, where $\Delta$ is the pushing distance. The visual display is updated immediately after the actual position is obtained.

3. IMPLEMENTATION AND EXPERIMENTAL RESULTS

The experiments were performed in an ambient condition. The system setup is shown in Figure 3. It consists of a Bioscope AFM (Vecco Inc., Santa Barbara, CA) with a scanner with a maximum $XY$ scan range of $90 \mu m \times 90 \mu m$ and a $Z$ range of $5 \mu m$. Some peripheral devices including a haptic device (Phantom, Sensable Company, Woburn, MA), a Multifunction Data Acquisition (DAQ) card NI PCI-6036E (National Instruments) and three computers. To speed up local scan, the DAQ card is mounted on a Linux computer running in real-time control system, and connected to the modified AFM controller. During manipulation, the tip motion command is transformed to voltage signal directly by the DAQ card and outputted to the modified controller. In this way, the tip motion can be controlled in real time with high-speed, which makes it possible to perform local scan on line without interrupting the manipulation process.

In this experiment, nano-particles are manipulated to validate the effect of OSD method. As shown in Figure 4(a), several latex particles with diameter around 110 nm were randomly distributed on a flat polycarbonate surface (scanning range $3.1 \mu m \times 3.1 \mu m$). Before nanomanipulation, a LSBM was performed to eliminate the random drift. Since random drift happened between the whole image and the AFM tip, the position error gotten from the LSBM existed between every particle and AFM tip. Thus instead of updating the visual display image with the new position of particles, the drift displacement was added onto the motion command of AFM.
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Fig. 4. Manipulating a nanoparticle on a polycarbonate surface with scanning range $3.1 \mu m \times 3.1 \mu m$. (a) Latex particle with diameter 110 nm on polycarbonate surface before manipulation; (b) Real time display on the visual feedback interface; (c) A new scanned AFM image after manipulation.

Fig. 6. Manipulating nano-particles with diameter 350 nm on polycarbonate surface. Scanning range: $11.13 \mu m \times 11.13 \mu m$. (a) Image before manipulation; (b) Manipulation result displayed in the real-time visual feedback interface; (c) True manipulation results obtained from a new AFM image scan.

As shown in Figure 4(b), one particle was pushed along the arrow direction. The indent in the rectangle is the visual displayed final particle position based on the behavior model. Since there are a lot of uncertainties under nano-scale, the visual display may not be true due to the modeling error. A LSAM was immediately performed after the manipulation. The position obtained from local scan is shown as the circle in Figure 4(b). Figure 4(c) shows a new captured AFM image after manipulation. The good match of these two pictures proves that the OSD method identified the actual particle position correctly. The scanning pattern in this experiment is generated as shown in Figure 5(a). The topography information of the scanning lines is shown in Figure 5(b). The actual position of the nano-particle can be easily identified based on the topography information along the scan lines as describe in Section 2.

Figure 4 shows the often happened situation in AFM based manipulation that the AFM tip is easy to slip over or slip away from the object. Without OSD method, a new image scan is repeatedly needed to find the actual position of the lost particle. With the assistance of OSD, the object’s actual position can be on-line obtained without a new image scan. The reliability of the visual feedback is greatly enhanced. Since only several lines are scanned during OSD method, this process can be real-time finished without interrupting manipulation. Operator can immediately know the result after each step of manipulation. Figure 6 shows the particles with diameter 350 nm are manipulated under the assistance of OSD. The real-time AFM image is displayed in the augmented reality interface as shown in Figure 6(b). A new scanning image after manipulation is shown as in Figure 6(c). The pictures show that the final result matches well with the display in the visual feedback interface. All of these experiments are finished continuously in a couple of minutes. From these experimental study, it can be seen that assembly of nanostructures using the AFM based nanomanipulation system becomes very straightforward and high efficient.

4. CONCLUSIONS

It is well known that the main difficulty of nanomanipulation using AFM is the lack of real-time visual feedback. Due to this reason, the problems aroused from random drift and modeling errors in the manipulation can not be solved as in the macro world. Thus any methods which can update the AFM image as close as possible to the real environment in real time will assist the operator to perform several operations without the need of a complete new image scan in between. The proposed OSD method provides a good solution to approach this goal.
Through the work of this paper, not only can the position error aroused from random drift be compensated, but the faulty visual display due to the modeling errors can be corrected on-line without interrupting the manipulation process, which greatly facilitates AFM based nanomanipulation. The experimental results shows the efficiency and effectiveness of AFM based nanomanipulation has been significantly improved.

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References and Notes

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