2-D Micro Particle Assembly using Atomic Force Microscope

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Abstract — In this paper, a micro particle manipulation system using Atomic Force Microscope (AFM) as the manipulator has been proposed. The size of the particles to be manipulated is approximately 1-2 μm. Optical Microscope (OM) is utilized as the vision sensor, and AFM cantilever behaves also as a force sensor which enables contact point detection and surface alignment sensing. A 2-D OM real-time image feedback constitutes the main user interface of the directly teleoperated operation system, where the operator uses mouse cursor and keyboard for defining the trajectories for the AFM controller. Particle manipulation experiments are realized for 2.02 μm goal-coated latex particles, and it is shown that the system can be utilized in 2-D micro particle assembling.

1 Introduction

By the recent advances on micro-mechatronics technology, micro sensors and actuators, high precision positioners, micro robots inside the nuclear plant pipes, etc. have become possible. Especially, imaging devices such as Scanning Probe Microscopes and Near-Field Optical Microscopes can provide imaging down to submicron and atomic scale at 2-D or 3-D. However, for constructing more complex micro/nano machines or devices by assembling micro/nano parts, necessary fabrication and manipulation technologies are still very immature at the scales less than 10 μm. Because, at these scales, micro/nano sticking forces become dominant to the inertial force, and a new robotics approach is indispensable. At this point, many researchers are trying to find new strategies for micro/nano assembly.

The micro assembly approaches can be classified depending on the utilized control approach as: *direct teleoperated*, *task-based teleoperated (semi-autonomous)*, and *automatic* assembly approaches. In the former approach (Figure 1a) [4], [1], [7] using monitoring tools and a master manipulator, a human operator directly manipulates the micro slave manipulator by considering the scaling effect of the micro/nano world. Such systems can realize tasks requiring high-level intelligence and flexibility. However, they are slow, not precise, not exactly repeatable, and engaged in many complex and challenging problems in teleoperation from macro to micro/nano world. Miyazaki et al. [4] proposed a two probe-based assembly of spherical latex particles with the diameter of approximately 2 μm in 3-D, and tried to construct a 3-D pyramid where they had problems of assembling the last top particle due to adhesive forces. Tanikawa et al. [7] developed a directly teleoperated two-finger micro hand like a chopstick for moving glass spheres in 3-D with the size of 2 μm.

On the other hand, autonomous systems where micro manipulator operates in a closed-loop control without any external intervention are fast, accurate and repeatable. These features are very important for the micro/nano-assembling applications where mass-production is aimed in the future. But, these systems are not completely realizable and reliable at present beacuse we do not have the exact knowledge of the micro/nano world physics and the enough sensory tools and actuators. Therefore this group of research is using *task-oriented teleoperation* approach [5], [2] as shown in Figure 1b. In such semi-autonomous systems, human operator only sends high-level task commands and micro manipulator realizes these tasks in an autonomous way. Thus, such systems can utilize advantages of both teleoperation and autonomous systems. However, the problems of autonomous control are still valid. Still reliable force and 3-D visual feedback, and position control are required for reliable fully automatic assembly. Codourey et al. [2] proposed a nanorobotics system where a micro/nano-tool is driven automatically for realizing simple tasks using visual servoing. They achieved positioning of 50 μm diameter diamond particles using a glass pipette with air pressure controlled picking and placing.

In this paper, as an initial step, a directly teleoperated 2-D micro particle assembly system which utilizes Atomic Force Microscope (AFM) cantilever tip as the micro manipulator/tool and force sensor is proposed. The particles are polyvinyl gold-coated latex particles with diameter $\leq 2.02\mu m$. As different from other works, the proposed system has the potential of also manipulating the nano objects by replacing the optical microscope imaging with the AFM non-contact imaging [6], and by the automatic contact detection. i.e. real-time force feedback, the deformation of the tip or particle is prevented.

The organization of the paper is as follows: at first, the

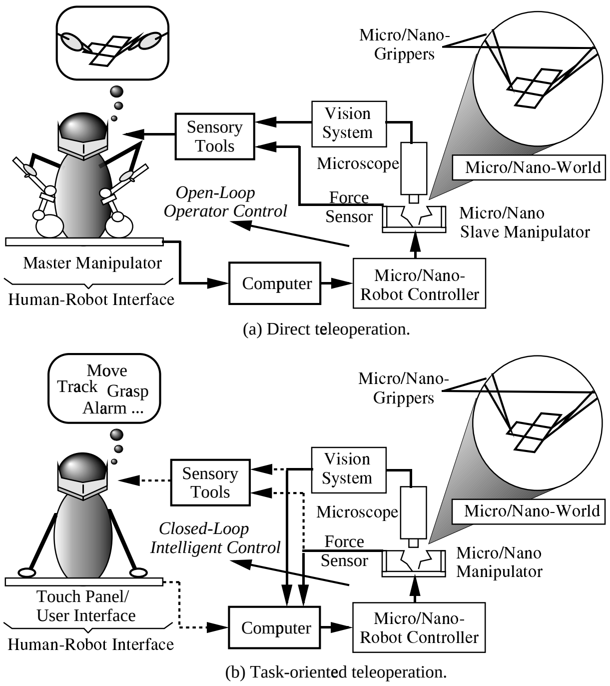

Figure 1: Direct teleoperation (a) and task-oriented (b) teleoperation system structures.

2-D micro particle assembly problem and our approach are defined. Then, the system setup and its components such as AFM, vision sensor, position control, etc. are explained. Next, micro particle assembly experiments are realized. Finally, conclusions and future directions are reported.

2 Problem Definition and Approach

Spherical polyvinyl gold-coated latex particles with sizes around $2.02\mu m$ (JEOL Datum Ltd.) are semi-fixed/absorbed to a Si substrate such that they are to be positioned by changing their xy positions. The particles are also called as *absorbates.* The operations are to be realized in open air conditions with high relative humidity. Thus, the sticking forces such as capillary and van der Waals are strong. Here, it is assumed that the electrostatic forces are negligible with respect to other forces.

In this paper, AFM tip which has a radius, R_t, around 30 nm is being utilized in contact pushing and pulling of the particles. As shown in the Figure 2, the forces between the tip and particle and particle and substrate should be controlled such that the particles can be moved while not sticking to the tip. In the figure, F_{ta} and f_{ta} correspond to the tip-absorbate attractive/repulsive interaction force and friction force respectively. F_{as} and f_{as} are the interaction and friction forces for the absorbate and the substrate. The angle between the contact point of the tip and particle center is represented as β. The tip is aligned with an angle α. The tip is placed above the substrate with the parking height equals to the radius of the particle R_a. Thus, it is assumed not to touch to and interact with the substrate. By this way, the tip is not deformed, and vertical sticking force between the tip and particle is reduced.

Here, not the tip base but the substrate is moved with a constant speed V, and the manipulation strategy is as follows: *use the fixed cantilever as a stopper while moving the substrate under the particle with a uniform speed.* Here, the constraint for realizing a reliable positioning is such that while the tip approaches to and retracts from the particle, or it fixes the particle, the particle should always stay in its original position. Considering this constraint, conditions for moving the particles can be given as follows:

- *at non-contact:* when the tip approaches or retracts from the particle, the particle should not stick to the tip and not move such that

$$\begin{aligned} F_{ta} sin\beta &\leq F_{as}, \\ f_{as} &\geq F_{ta} cos\beta, \end{aligned} \qquad (1)$$

- *at contact:* when the tip contacts with the particle the resulting pushing or pulling force should be enough to fix the particle without breaking the tip or particle such that

$$\begin{aligned} f_{ta} cos\beta + F_{ta} sin\beta &\geq F_{as}, \\ f_{as} &\leq F_{ta} cos\beta - f_{ta} sin\beta. \end{aligned} \qquad (2)$$

The aim is to design the control parameters such as the contact point, cantilever mechanical properties, particle-substrate friction, adhesion forces, humidity level and motion speed so that the above conditions can be held.

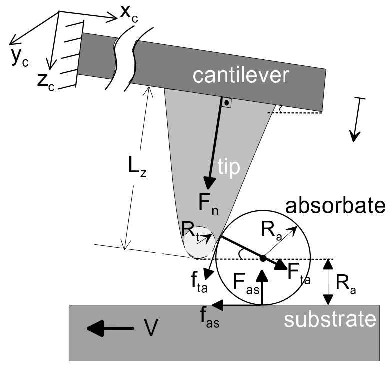

Figure 2: Positioning of the micro particles using the AFM tip as the manipulator.

3 System Setup

A direct teleoperation control approach is selected where an operator determines the trajectories to be moved. The

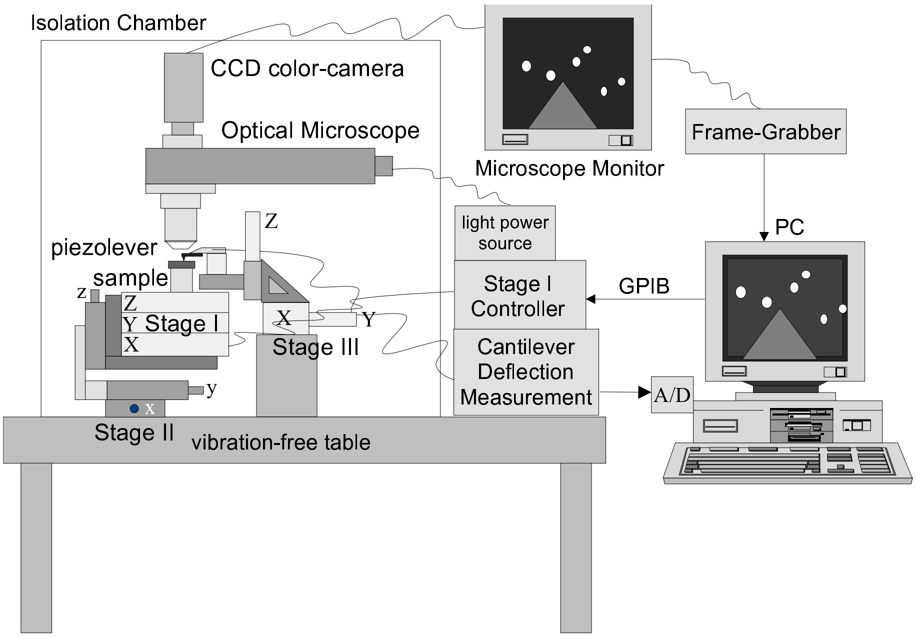

Figure 3: Overall system setup for the micro particle assembly.

overall system is shown in Figure 2 and the parts of the system are explained at following.

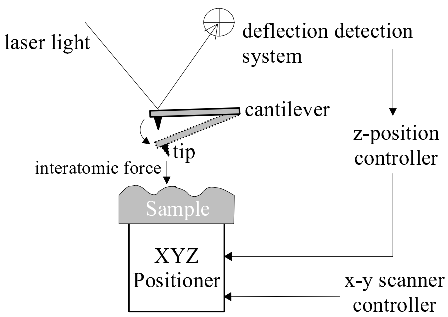

Figure 4: The basic structure of a conventional AFM.

3.1 AFM as the Manipulator and Sensor

The basic structure of a conventional AFM system is shown in Figure 3. The very sharp cantilever tip atoms are interacted with the sample atoms by moving the sample (or cantilever) in the z-direction. The interatomic force $F_n(t)$ which is perpendicular to the cantilever is attractive or repulsive, and the resulting typical deflection curve of the cantilever $\zeta(t)$ depending on the tip-sample distance $h(t)$ is shown in Figure 5. If the sample is moved slowly, i.e. the cantilever is at equilibrium at each point, then

$$F_n = k_c \zeta, \tag{3}$$

where k_c is the known cantilever spring constant. Thus, the tip-sample force can be measured by measuring ζ. Instead of a laser interferometry-type deflection detection system, ζ is measured by a Wheastone bridge-based deflection measurement electronics in our system as shown in Figure 2 since a piezoresistive cantilever (Park Scientific Instruments Co.) [3] is used. Thus, the output of the bridge is a voltage difference V_{out}, and the nanometer value of the ζ is computed from the below equation:

$$\zeta = SG_2(G_1 V_{out} + V_{off}), \tag{4}$$

where $G_1 = G_2 = 100$ are the amplification gains, V_{off} is the offset voltage which is needed when there is an offset depending on the different resistance values of the cantilevers, V_0 is the bridge voltage, and S is the constant scaling ratio which is calibrated for each cantilever previously.

Using the Eq. (3) and $F_n(t)$ vs. $h(t)$ relation curve, if a reference ζ^* is set at the contact linear region, then the z-stage is moved until detecting this point, and the (x, y) positions are scanned and at each point the same reference is tracked. Thus, the surface 3-D topology image can be held. This method is called *Contact Imaging Mode*.

These properties of the AFM can be utilized in following ways:

- the alignment error of the substrate can be compensated by getting a contact 3-D topology planar image of the substrate along single x and y lines where there is no particle,
- the contact point between the tip and the particle can be detected by measuring ζ since it will change if there is a contact.
- the initial z-position of the tip above the substrate is set by contacting and retraction of the sample to the tip.

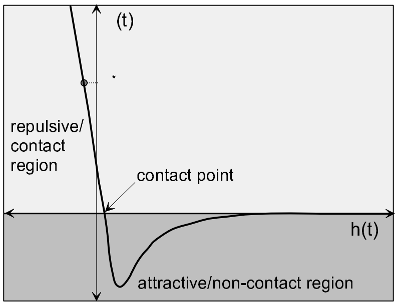

Figure 5: The typical cantilever deflection, i.e. inter-atomic force, and tip-sample distance relation.

3.2 Vision Sensor: Optical Microscope

A reflecting light-type Optical Microscope (OM) (Olympus Co.) is used as the top-view vision sensor. The specifications of the microscope is given in Table 1. A color camera (Sony Co.) on the OM is connected to a Matrox Co. Meteor frame-grabber which enables real-time color image viewing of the micro world on the PC screen with the range of 640 × 480 pixels in the image frame, (x_p, y_p), and approximately $57 \times 45 \mu m^2$ in the world coordinates, $(x_{\mu m}, y_{\mu m})$. Hereafter, the world coordinates mean the coordinate frame for the AFM positioner x-y motion space. The image and world coordinate frames are given in Figure 6. In the case of linear mapping between both spaces, $x_{\mu m} = \alpha_x x_p$ and $y_{\mu m} = \alpha_y y_p$ where $\alpha_x = \alpha_y \approx 95nm/pixel$ are constant x and y scaling constants. However, during the experiments, it is observed that there is also some rotaion in the coordinates due to the orientations of teh camera, stage and sample surface. Therefore, a calibration process is needed before the experiments in order to map (x_p, y_p) to $(x_{\mu m}, y_{\mu m})$ which is explained later.

working distance	$25mm$
maximum resolution	$\approx$ $500nm$
image resolution	$\approx$ $95nm/pixel$
lens magnification	×80
lens numerical aperture	0.5
overall magnification	×5000 (on monitor)
base stand	5DOF (manual)

Table 1. Optical Microscope specifications.

3.3 User Interface

The user interface constitutes of the real-time display of the top-view images from the camera mounted on the OM. The operator uses the mouse cursor and keyboard for defining the tasks for the micromanipulator (AFM) controller. At present there are three main tasks:

- *Task 1 (T1)*: position the tip above the substrate,
- *Task 2 (T2)*: point-to-point motion,

At the task T1, the tip is set to the height of R_a above from the substrate automatically. For this, the substrate is moved along the z-direction until touching to the tip,

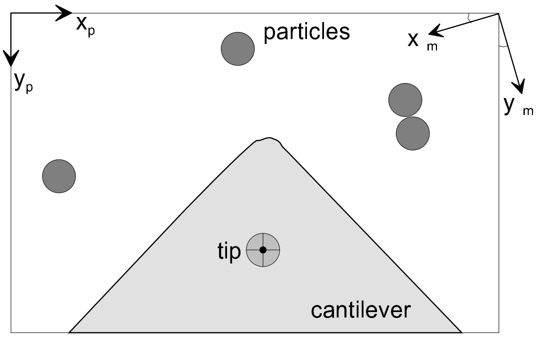

Figure 6: Optical microscope top view, and image and positioner coordinates.

i.e. tip deflection is measured as ζ_{set}, then retracted back to the z-position given as $z = z_{final} - h_{set}$ where $h_{set} = R_a$ as shown in Figure 7.

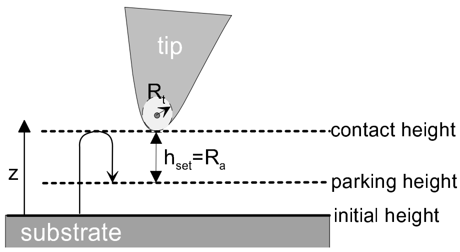

Figure 7: Tip parking height setting above the substrate.

In the task T2, the operator points the first point and the target point to be moved by the mouse cursor. Then the positon controller automatically moves with the amount of relative distance between the two points. This operation is the essential part of the positioning and pushing or pulling operations.

3.4 Position Control

For the manipulation of the particles and initial settings, three different stages are utilized as shown in Figure 2. Their specifications are given in Table 2. The fine positioning XYZ piezoelectric stage (Physick Instrumente Co.)is utilized during the automatic particle assembly control. The main motion of the stage is point to point motion. Here, the problem with the stage controller is such that the x and y axes cannot be moved simultenously. Therefore, following point-to-point motion strategy is introduced as shown in Figure 8 where

$$\begin{aligned} x_i &= x_1 + s_x \Delta cos\theta i, \\ y_i &= y_1 + s_y \Delta sin\theta i \end{aligned} \quad (5)$$

where $i = 1, \ldots, N$, $N = \Delta L/\Delta$, Δ is the predetermined motion step resolution. For $\Delta x = x_2 - x_1$ and $\Delta y = y_2 - y_1$, s_x, s_y, θ and ΔL are computed as

$$\theta = tan^{-1}(|\Delta y|/|\Delta x|),$$
$$s_x = \Delta x/|\Delta x|,$$
$$s_y = \Delta y/|\Delta y|. \quad (6)$$

Thus, at each i^{th} step, firstly x_i then y_i is moved.

	Stage I	*Stage II*	*Stage III*
Actuator	piezoelectric	electro-strictive	bearing
Resolution	$10nm$	$\approx 40nm$	$10\mu m$
Range	$100\mu m$	$30\mu m$	$18mm$
Control	closed-loop	open-loop	manual
Hystheresis	$< 0.1\%$	$< 4.8\%$	
DOF	XYZ	XYZ	XYZ

Table 2. Specifications of the used stages.

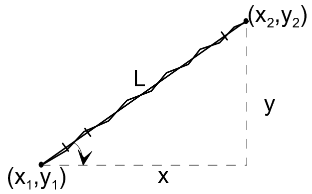

Figure 8: Point-to-point motion strategy.

3.5 Coordinate Frame Calibration

Image to world coordinates transformation constitutes of scaling and rotation transformations, and it is calibrated before the experiments.

From the tests, the rotation angles ϕ and γ for the x and y axes, and scaling factor s are computed. Then, the pixel to μm position trasformation is as follows:

$$\mathbf{x_{\mu m}} = \mathbf{A}\mathbf{x_p},$$
$$\mathbf{A} = \begin{bmatrix} -scos\phi & ssin\gamma & 640scos\phi \\ ssin\phi & scos\gamma & -640ssin\phi \\ 0 & 0 & 1 \end{bmatrix},$$
$$\mathbf{x_{\mu m}} = [x_{\mu m} \quad y_{\mu m} \quad 1]^T,$$
$$\mathbf{x_p} = [x_p \quad y_p \quad 1]^T. \quad (7)$$

4 Experiments

As the first experiment, the contact point detection is tested. The calibration parameters of the experiments are $s = 0.095$, $\phi = 9^o$, $\gamma = 1^o$, $R_a = 2.02\mu m$, anc $R_t = 30nm$. The humidiy level of the experiment room is around 60%. A particle is moved along a line as shown in Figure 9 that passes through the tip center. Then, $\zeta(Volt)$ during the motion is given in Figure 10. In the figure, there is an attractive force peak where ζ becomes positive, and then the contact and repulsive region where ζ goes down until to the set point $-1V$. At the set point, the stage stops automatically.

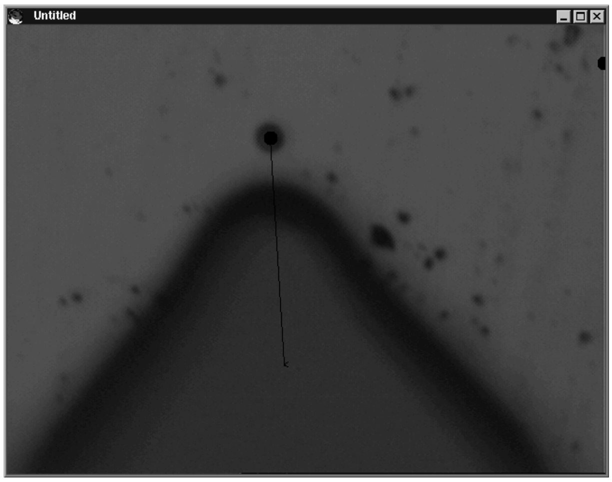

Figure 9: The particle trajectory determined by the user.

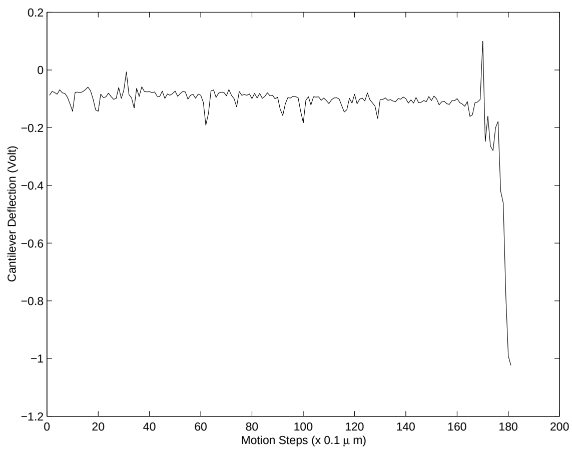

Figure 10: The cantilever deflection is measured for detecting the contact between the tip and particle automatically.

As the next experiment, pushing of a particle is realized where the image sequences can be seen in Figure 11. The particle is added to a line of particles successfully.

5 Conclusion

In this paper, a micro particle manipulation system using Atomic Force Microscope (AFM) as the manipulator has been proposed. Modeling and control of the AFM cantilever tip and particle interaction has been realized for moving particles with sizes around 1-2 μm on a Si substrate in 2-D. Particle manipulation experiments are realized, and it is shown that the system can be utilized in 2-D micro particle assembling. As the future work, the manipulation operations will be realized using task-based teleoperation control and the interaction forces among the tip, particle and substrate will be analyzed.

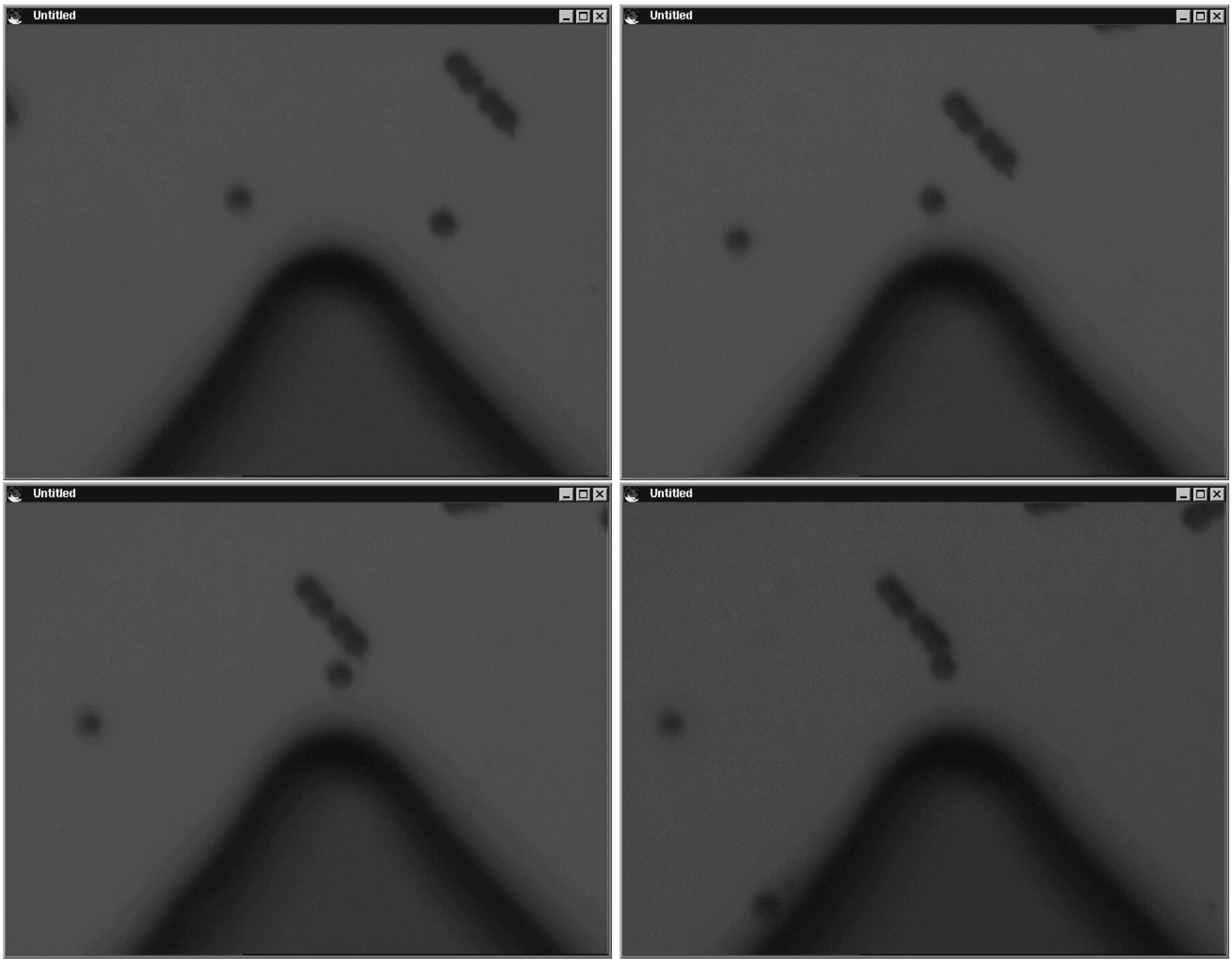

Figure 11: Image sequences of pushing a particle by the steps shown above beginning from the initial position (uppermost left) to the last configuration (bottom right).

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