Micromanipulation and Robotic Technology

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Abstract

Micromanipulation is needed for assembly and maintenance of micro machines and their parts. Micromanipulation is also important for bio-science and bio-engineering field. Yet, the design and control methodology for micromanipulation is not well established. In this paper, we summarize research topics and basic technologies which will be essential for the micromanipulation. Moreover, we introduce our approach and new direction in this field.

1. Introduction

Research on the micromachine has been promoted and basic elements, such as microsensors, microactuators, and micromechanisms have been developed together[1]. Yet, most of the microfabrication method is based on the conventional lithography or the other two-dimensional fabrication methods. Generally, it is difficult to manufacture three-dimensional microstructures. Some new fabrication methods have been proposed such as the LIGA process and stereo lithography, to make three-dimensional microstructures. However, it still seems difficult to integrate sensing, actuating, and mechanical parts to build up a complicated three-dimensional microsystem. To make the three-dimensional microsystem, an assembly process will be required to some extent. Moreover, modification and maintenance of the microsystems are needed.

On the other hand, in the field of bio-science and bio-engineering, anatomic operations are frequently performed. Operators manage to manipulate the biological objects by the micromanipulators with the two-dimensional image from the optical microscope. However, operation of the micromanipulator in the three-dimensional micro/nano world is quite difficult. From these points of view, three-dimensional high speed micromanipulation is needed as a fundamental technology.

Micromanipulation is broadly classified into the following two types:

(A) contact type;
(B) non-contact type.

Manipulation environment is classified as follows:

(i) air;
(ii) liquid;
(iii) vacuum.

Environment of the micromanipulation depends on the object's property, size, and observation method. In this point of view, micromanipulation can be classified as Fig.1. Research topics on the micromanipulation is shown in Fig. 2, and summarized as follows:

(1) observation;
(2) actuation;
(3) measurement;
(4) physical phenomena and scaling issues
(5) design;
(6) fabrication;
(7) calibration;
(8) control;
(9) transportation, alignment, and fixation;
(10) communication;
(11) human-machine interface.

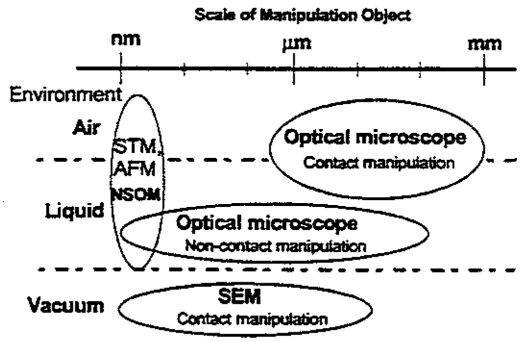


Figure 1. Classification of micromanipulation based on the environment

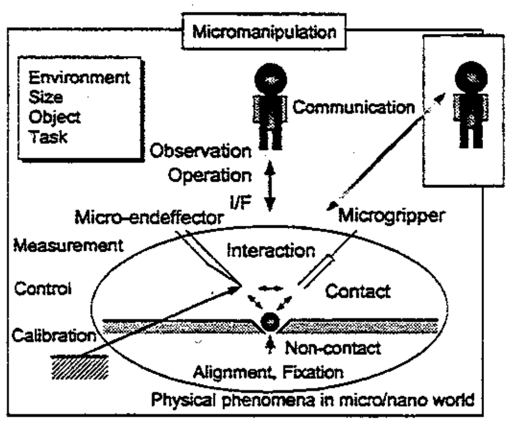


Figure 2. Research topics on the micromanipulation

2. Physical Phenomena in Micro/nano World

When we design a system, we should pay attention to the size and environment condition. Most of the control engineers are familiar with the modeling method based on the Newtonian mechanics. However, physical phenomena in the micro/nano world are completely different from those in the macroworld. Modern control theory depends on the modeling of the system so much. So, when we design the microsystem including its controller, Physics in the micro/nano world is very important. Thermal, optical, electrical and magnetic effects will change or become dominant when the objects are miniaturized. Conventional studies on the microsystem didn't care for physical phenomena in the micro/nano world so much, and as a result, system performance were degraded or became inefficient.

Although many kinds of microsystems have been developed, the design and control methodology of them is not well established. Difference of dimensions between the macro and micro/nano world causes difference of the influential physical phenomena, motion of the objects, and relative change of the system performance between those worlds. To realize a three-dimensional high speed micromanipulation system, it is important to understand the physical phenomena in the micro/nano world. In the following chapter, we introduce how to realize high speed micromanipulation in the air.

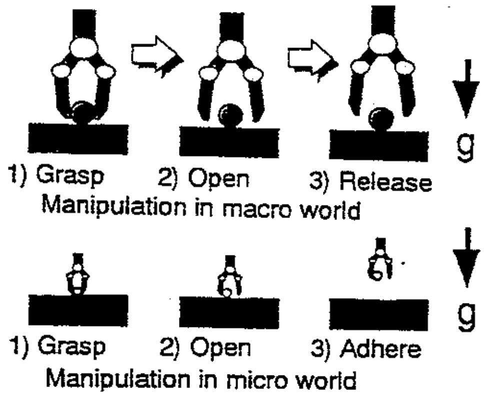


Figure 3. Difference of manipulation

3. Micromanipulation in the Air

3.1 Problems

Here we consider the contact type micromanipulation in the air. The following are the typical movement of this case.

(A) lift up (hold, attach, stick, vacuum, etc.);
(B) place (release, attach, stick, vacuum, etc.);
(C) arrange (lift up and place, slide, rotate, etc.);
(D) push (hold, twist, cramp, deform, etc.).

Here, manipulation objects are supposed to be of the micron order. Then the adhesive forces are dominant in manipulating the micro objects, compared with the gravitational force [2-4]. Research on the effect of the following adhesive forces are promoted:

(1) van der Waals force;
(2) electrostatic forces;
(3) surface tension force, hydrogen bonding force, etc.

Balance of these forces is depend on the environment condition, such as humidity, temperature, surrounding medium, surface condition, material, and relative motion. If the objects to be handled are miniaturized (ex: less than 100μm), surface forces work as the adhesive force. These forces aren't negligible in the micro/nano world manipulation (Fig. 3). Microparts adhere to the grip surface by the adhesive forces. Adhesive forces will disturb the handling operation in some situation. We cannot manipulate them as we expected from macro world experiences. Thus, adhesive force reduction [3-5] is very important to achieve high speed micromanipulation.

When we manipulate micro objects in the humid air condition, typical adhesive forces are van der Waals force, surface tension force (capillary condensation of water), and electrostatic force. These forces are calculated for the sphere that contacts with the plate [3]. Here, the sphere is made of SiO_2, and the plate is made of Si. These adhesive forces are dominant compared with the gravitational force in the microworld.

If we can reduce the adhesive forces, manipulability for (A), (B), and (C) of a micro object will be improved. To improve manipulability for (D) of the micro object, force sensor is important.

3.2 Strategies of Adhesive Force Reduction

We have proposed basic strategies to reduce the adhesive forces[3]. Basic strategies to reduce the adhesive forces can be summarized as follows (Fig.4).

(i) Coating with material on the surface: Van der Waals force is reduced.
(ii) Hydrophobic treatment of the surface: Reduction of adsorbed water molecules on the surfaces
(iii) Roughness change: Van der Waals force is reduced.
(iv) Electrostatic force change: Static charge elimination
(v) Temperature change: Move out the capillary condensation of water and adsorbed water molecules by heating
(vi) Pressure change: Positive pressure generation by an air pump or temperature change[5,6]

Koyano and Sato proposed to overcome the adhesive force by the handling skill of sliding and inclining tool[7]. They also proposed to use two tools. In these case, configuration of the tool tip is very important. Moreover, position control accuracy or contact force evaluation is important.

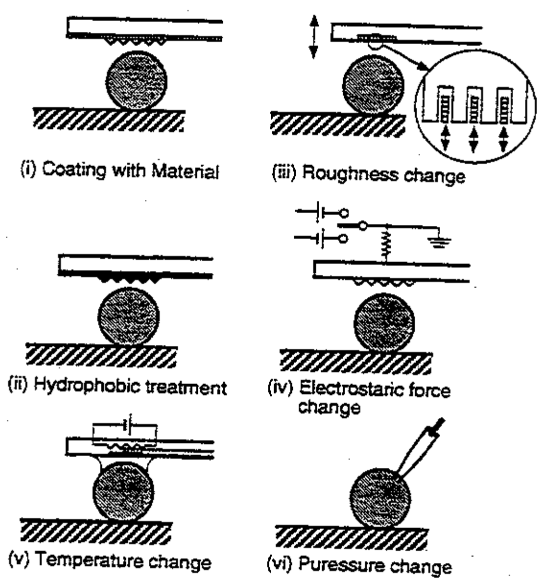


Figure 4. Strategies for reduction/control of adhesive force

3.3 Micro Pyramids

If the contact area is decreased, it is quite effective to reduce the van der Waals force. From the previous analysis and experiments, surface roughness has great influence on reduction of the van der Waals force[3]. Let's consider the van der Waals force between the ideal plane sphere and plate. The surface of the plate has roughness. The van der Waals force can be calculated based on the volume integration by assuming the additivity of the interaction between atoms. When the roughness of the plate surface increases, the space occupied by atoms on the surface decreases. Here, we assume the roughness of the plate surface is small compared with diameter of the sphere. It is easy to imagine the van der Waals force is reduced by increasing the surface roughness. We carried out experiments to evaluate the effectiveness of the surface roughness. It was clear to see that we can reduce the adhesive force by increasing the surface roughness.

A sharp electrode is effective to generate high electric field. If the sharp electrodes are made on the surface of the endeffector, the electrostatic force is reduced easily. To reduce the adhesive forces, we propose to make sharply edged projections on the grip surface(Fig. 5). We call these sharply edged projections as the micro pyramids[4]. The micro pyramids are coated with the thin film layer of the precious metal(Ex: Au). Thin film of the precious metal is hard to be oxidized. It is grounded and can be used as the sharp electrode in the air. A sharply edged structure is also effective to reduce the van der Waals force, because the contact area is decreased. By the adhesive force reduction, manipulability of the micro object was improved very much. The proposed method is based on the strategies (iii) and (iv) in Fig. 4.

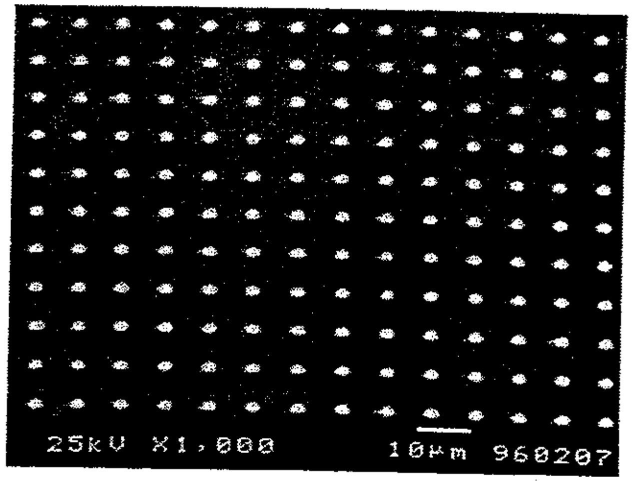


Figure 5. SEM photograph of the micro pyramids on the endeffector surface

3.4 Micro Holes

We have developed the other type of micro endeffector to reduce the adhesive forces based on the strategies (v) and (vi) in Fig. 4. As a method to generate the positive pressure, we can use the air pump. On the other hand, to move out the capillary condensation of the water and adsorbed water molecules, we can use a heating device. So, we tried to generate positive pressure in the micro holes by the temperature difference[5].

The basic strategies (i) - (vi) can be integrated. According to the manipulation environment, we can consider several types of micro endeffector. Especially, micro pyramid type and heating type can be integrated easily, and we can expect each advantages. Figure 6 shows the concept of the integrated micro endeffector to reduce the adhesive forces effectively.

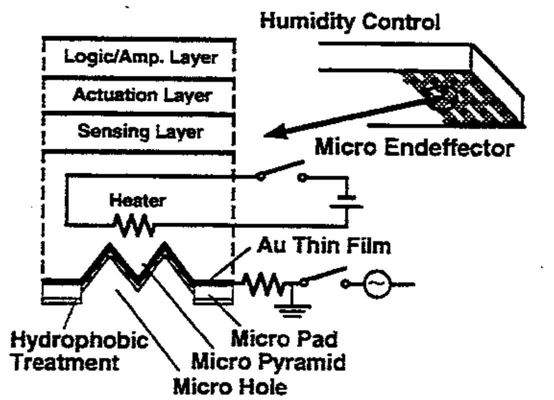


Figure 6. Concept of the integrated microendeffector

3.5 Example of the Integrated Micro Endeffector

Based on the analysis and basic experiments, we designed a micro endeffector that is set at the tip of the microgripper. It has the micro pyramids and integrated force sensor. We designed a force sensor based on the piezoresistivity effect since it has good linearity. We made a micro endeffector with the piezoresistive force sensor and the micro pyramids on the (100) Si cantilever [4].

4. Micromanipulation in the Liquid [8]

4.1 Manipulation of Biological Objects

Recently, bio-science is progressed so much with the advancement of the bio-technology. Bio-technology can be classified into gene engineering, cell engineering, and development engineering. In these research fields, the micro/nano manipulation, mass production, repetitive processing, and high speed and high precision processing in the liquid are required, since we have to deal with the biological objects. For the breakthrough in these fields, integration of the distributed research fields and system technologies is important. At this moment, conventional robotics has potentiality for the breakthrough in the bio-engineering. We should integrate the robotics and bio-engineering. We call this field of study as the bio-robotics.

Basic technologies of the bio-robotics are manipulation technology, microsystem technology, visualization technology, human interface technology to improve operability, automation technology, and so on. Especially, micro/nano manipulation of a DNA molecule, microbe, animal or plant cell, and embryo is important. However, research is not enough at present. Here, we present new direction of the bio micromanipulation in the liquid, and introduce new methods to improve operability and working efficiency.

4.2 New Technologies for Bio Micromanipulation

As an example of the contact tasks in the liquid, nuclear transplantation or embryo culture requires those technologies. Most of the bio micromanipulation tasks are performed in water solution. Thus, compared with the general manipulation tasks in the air, we have to consider not only the gravitational force but also the buoyancy, fluid force from flow, Brownian motion, interactive forces in the micro/nano world such as Van der Waals force, electrostatic force depending on the surface electrons. Moreover, size of each manipulation object is in micron order, it is quite difficult to recognize its configuration and to manipulate it freely. Automation of manipulation is quite difficult and skills are required. In the contact manipulation, the internal force is generated at the object. It is important to control the internal force precisely. The operability of the contact manipulation depends on the fixation of the object. From these point of view, we summarize the basic strategies to improve the operability of the bio micromanipulation as follows[8] (Figure 7 shows the operation improvement methods.).

(i) Utilization of the fixation device (Bio-aligner)

To improve work efficiency and operability in solution, fixation of the object is required. Once the object is fixed at the desired location, we can easily realize contact manipulation automatically. At present, polylysine or micro pipette is used for fixation. Fixation by the polylysine is easy, but this method is not reversible. Automation of the micro pipette operation is difficult. So, we need to develop a new device in a different way.

(ii) Presentation of visual information

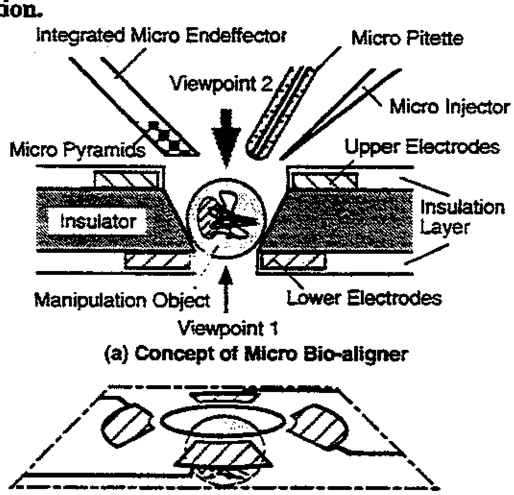
It is difficult to recognize an object from top or bottom by the microscope. Multi directional images and 3D image of the object and working environment are useful. However, if the operator looks at the different place and doesn't aware the problems, he/she may destroy the object or the device. To avoid accidents, it will be effective to make alarm sound or to superimpose an appropriate CG image on the monitor.

(iii) Measurement and presentation of force information

It is effective to measure the force acting at the object. Moreover, force or tactile display with sound generation will be effective to improve operability. We can apply virtual reality technology for presentation of local information in the microworld to the operator. Human being is very sensitive to the frequency change of the sound. So, it will be effective to present force information as the frequency change of the sound.

(iv) Realization of autonomous function

Micromanipulation tasks are versatile. So, it is difficult to realize a full automation system. We should start from classifying the basic operation. Most of the contact manipulation, such as nuclear transplantation, is performed by the human operator by hand with the microscope. We can't expect quick response nor precise and repetitive operation by hand. So, we should realize shearing of the autonomous function and manual operation.



(a) Concept of Micro Bio-aligner

(b) Free Viewpoint Selection and Virtual Image

Figure 7. Operation improvement methods

4.3 Operation Improvement by the Bio-aligner

It is important to fix the object in solution to reduce the work load of the operator and improve the operability. If the object is fixed in solution easily, it will become easy to control internal force applied at the object. Moreover, automation of the contact tasks for the object will become easy. If the location of the object is not known exactly, the system must measure the location of the object, otherwise automation is impossible. We have studied on the image recognition of the object, however, it takes time. If the object is easily fixed at the exact location, it helps to realize automation of the contact manipulation tasks. This also leads to the mass production. However, conventional methods are not suitable for bio automation.

We have proposed the bio-aligner. Desirable function of the bio-aligner is summarized as follows:

(a) it can fix the object
even if the external force is applied;
(b) it can inhibit adhesion of the object;
(c) it can control position/ orientation of the object.

Generally, many different kinds of forces are acting on the cell in solution such as the gravity, buoyancy, resistance force from viscosity of the fluid, Brownian motion, interactive forces in the micro/nano world such as Van der Waals force, electrostatic force depending on the surface electrons. Moreover, if there is a flow, fluid force will disturb its motion. To control the biological object, we need to control external force. To apply external force to the object, the following methods can be used.

(1) Electric field
Coulomb force (DC)
Dielectrophoretic force (AC) [9-12]
(2) Supersonic [13]
(3) Laser tweezers [14]
(4) Fluid flow of solution [15]

(2) and (3) require position information of the object, and the sensing system is needed for automation. (4) will disturb the environment with the fluid flow. We can simplify the system by using the electric field. In case of using coulomb force, convection caused by electric osmosis, polarization of the electrode, and electrolysis will occur. So, we proposed to use dielectrophoretic force to control the object.

Figure 7 (a) shows the conceptual figure of the bio-aligner. If the cell has the different dielectric constant, dielectric polarization will occur in the cell by applying the electric field. So, if we make the electric field gradient, we can transport the cell in non contact manner. Moreover, by applying the AC electric field of MHz order, we can reduce electric osmosis and electrolysis.

We made a simplified macro model of the bio-aligner and did preliminary experiments. Upper hole diameter is about 300 μm. Thickness of the plate is 100 μm. A micro bead(diameter: 100 μm) is fixed to the wall by applying the high frequency electric field (1 MHz) between the electrodes. There was no electrolysis. By changing the electric field pattern frequently, we observed the vibration motion of the bead. We can switch the motion of bead rapidly. The experimental results agreed with our FEM analysis.

The proposed method can be easily expanded to the three dimensional case. If we allocate the electrodes in the 3D space, and controlling the electric field pattern so as to generate the rotational change of the electric field, we will be able to control the orientation of the object and also to avoid non reversible stick.

5. Three-Dimensional Micromanipulation

5.1 Problem of the Position Accuracy

In case of manipulating a micro object, such as a cell or microbe, manipulation area for one object is micron order. When we array the multiple objects in plane, the moving area of the micromanipulator is more than millimeter order. Moreover, if we change the endeffector and transport the objects, it will become more than centimeter order. Thus, micromanipulator must have moving mechanism more than centimeter order and position accuracy of nanometer order. The micromanipulation system must achieve this requirements in the three-dimensional space.

5.2 Improvement of Position Accuracy

Absolute position accuracy in the three-dimensional space is quite important to perform micromanipulation tasks safely and smoothly. However, it is very difficult to guarantee the absolute position accuracy in submicron order for all working area, because of the alignment error and thermal deformation. Especially, if the endeffector of the micromanipulator is changed, we have to calibrate the positioning system again to guarantee the absolute position accuracy. So, calibration method against the miss alignment of the system components and tool exchange is important. If we can calibrate the system in the three-dimension easily, we can realize automation and safe manipulation. We have proposed the three-dimension calibration method with the micromanipulation system [16]. On the other hand, visual feedback is effective for the micromanipulation with the microscope. We can observe the manipulation object by the microscope. Some microscope can give us three-dimensional information of the environment, and we can utilize it to realize automation and safe manipulation.

We can summarize the methods to improve the position accuracy of the micromanipulator as follows.

(1) Calibration [16]
(2) Visual feedback [17,18]

5.3 Human-machine Interface

Visualization is important to improve the speed and accuracy in manipulation and decision making. Total physical area under the microscope is wide, but the field of manipulation is narrow and distributed. So, magnification and reduction of the object's image are frequent. In such cases, visual user interface of the micromanipulation is quite important. There has been proposed an auto focus system [18,19], image database [20], and graphical user interface [21] to improve the operation of the micromanipulator.

6. Conclusions

In this paper, we classified the micromanipulation and introduced the basic research topics and fundamental technologies of the micromanipulation. Environment of the micromanipulation is versatile. Here we focused on the contact type micromanipulation in the air and in the liquid. Micromanipulation in the vacuum is also important, and there are so many research works. Moreover, there are non-contact type micromanipulation methods. Actually, we have studied non-contact manipulation by the dielectrophoresis and the optical laser tweezers. But we have to omit it because of page limitation. In any case, it is important to enhance the physical phenomena in the design and control of the micromanipulation system.

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