Survey of Nanomanipulation Systems

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Abstract

Nanomanipulation as a new emerging area enables to change, interact and control the nano scale phenomenon precisely. Nanomanipulation systems are surveyed in this paper. Nanomanipulation approaches are grouped according to their starting point, utilized process, operation type, manipulation environment, interaction type, etc. Main components of such systems such as nanomanipulators, nano physics, sensors, actuators, and control are given in detail. Problems are defined and possible solutions are proposed. Moreover, possible applications in biotechnology, computer technology, material science and micro/nanotechnology are reported.

1 Introduction

Nanotechnology which aims at the ideal miniaturization of devices and machines down to atomic and molecular sizes has been a recent hot topic as a promising high-technology for the forthcoming century. By precise control of atoms, molecules or nano scale objects, new sensors and man-made materials, tera-byte capacity memories, micro scale robots and machines, DNA-computers, quantum devices, micro scale distributed intelligence system devices with integrated sensors, actuators and communication tools, etc. would be possible within the near future. However, for new nanotechnology products, still there are many challenges to be solved, and nanomanipulation is one of the key challenges in the nano world. Chronologically, first nanomanipulation examples start at 1990 [1], and accelerates after 1995 by increasing potential application areas. But, this kind of research is still immature since the physical and chemical phenomenon at this scale has not been completely understood, intelligent automatic precision manipulation strategies are not developed, and the specific tools for the specific applications have not been defined or designed systematically. Thus, the purpose of this paper is to survey the existing nanomanipulation systems, define challenging research problems and propose some possible solutions.

2 System Structure

Nanomanipulation could be defined as the manipulation of *nanometer* size objects with a *nanometer* size end-effector with *(sub)nanometer* precision. By manipulation, it is meant that nano objects are pushed or pulled, cut, picked and placed, positioned, oriented, assembled, indented, bended, twisted, etc. by controlling external forces with sensory feedback. A basic nanomanipulation system is illustrated in Figure 1. Grouping of nanomanipulation systems can be conducted based on the utilized starting point, manipulator and object interaction process, utilized nano manipulator interaction, and operation technics as given in Figure 2. Components of these systems are given in detail at below.

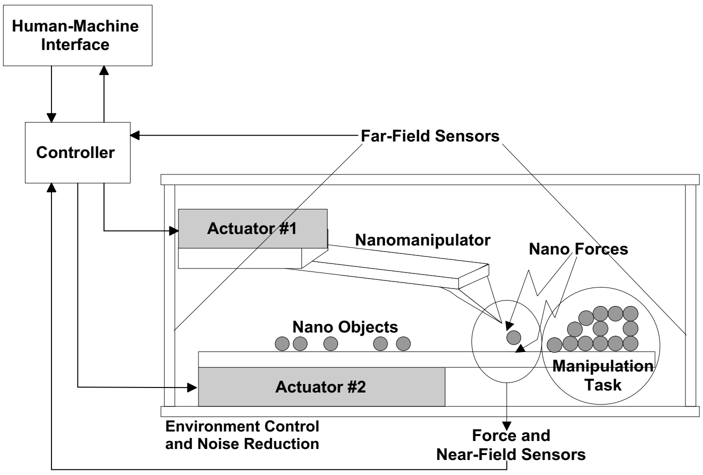


Figure 1: Basic structure of a generic nanomanipulation system.

3 Nanomanipulators

For applying an external force, nanomanipulators can be designed as contact or non-contact type. Atomic Force Microscope (AFM) and Scanning Tunneling Microscope (STM) probes are the most widely used nanomanipulators. Using a STM probe, manipulation of atoms or molecules by applying voltage pulses between the probe

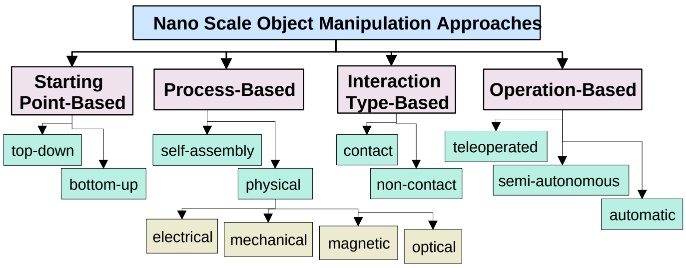


Figure 2: Grouping of nanomanipulation systems depending on starting point, utilized process, manipulator and object interaction type, and utilized operation technique.

and a conducting sample was realized at 4 K^o [2] in 1991, and even at room temperature [3] recently. AFM probe can only realize more mechanical tasks as shown in Figure 3 such as push and pull [4], [5], [6], [7], [8], cutting, indenting, etc.

Using one AFM probe, simple 2D tasks can be realized. As examples of these tasks, micro/nanoparticle pushing [9] and indenting [10] are displayed in Figure 4 and 5. For more complex manipulation tasks such as pick and place, multiple probes as shown in Figure 6 [11], [12], or chemically activated and controlled probes are needed. A possible scheme for a chemically recognition based pick and place is illustrated in Figure 7. As possible grippers of multiple probes, multi or single walled carbon nanotubes can be attached to the AFM probe tips with an angle [13]. This is very attractive since nanotubes can be very small in diameter such as 1-50 nm, their shapes are well-defined, and they are mechanically strong. 3D nanomanipulation is being challenged by several groups [14], [15] and [16].

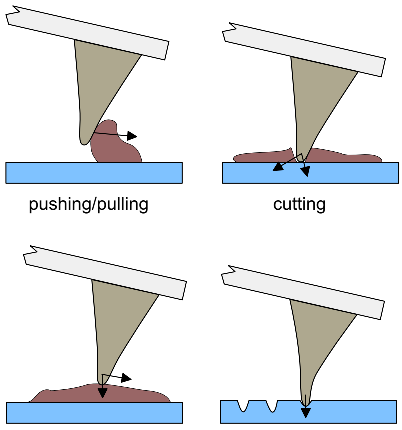
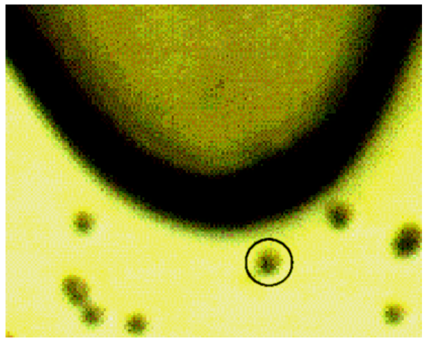


Figure 3: Possible mechanical manipulation tasks using an AFM probe as a nanomanipulator.

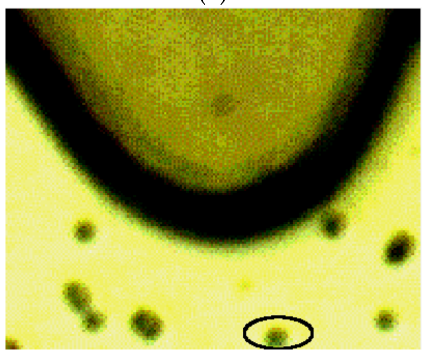
Optical tweezers is a non-contact manipulator, and applies loads in the order of pN on the samples. Therefore, they are widely utilized for bio-nanomanipulation applications where the samples are very fragile. By focusing the laser beam to a bead, DNA [17], RNA [18], chromatin fiber [19] or any other biomaterial can be manipulated in almost 3D. Bustamante *et al.* stretched and twisted DNA and proteins using the optical tweezer and glass pippette. Foubert *et al.* [20] cut porphyrin rings using AFM and optical tweezers. Moreover, Bennink et al. manipulated double stranded DNA [21].

Scanning Near-Field Optical Microscope (SNOM) probe can be utilized as a manipulation tool. Obermuller *et al.* [22] thinned down quantum dots by SNOM probe based scratching.

Above manipulation systems mostly utilize only one type of manipulator in a given system. For more advanced systems and dexterous manipulation tasks, these manipulators should be integrated as in Figure 6. In the literature, first attempts are made by integrating AFM



(a)



(b)

Figure 4: Pushing a 242 nm radius latex particle with an AFM probe (top view optical microscope images): (a) before and (b) after pushing [9].

with optical tweezers for DNA manipulation [23].

4 Sensing

Main sensors for nanomanipulation are visual and force sensors. Moreover, depending on the specific application, temperature, liquid flow and chemical sensors could be also useful.

4.1 Nano Scale Imaging

As the possible visualization tools, the microscopes shown in Figure 8 are mainly utilized during nanomanipulation. STM and AFM are the most common imaging tools as near-field microscopes. STM measures the tunneling current between its metallic probe and sample while scanning in x-y direction. On the other hand, AFM has a cantilever with a very sharp tip such that the

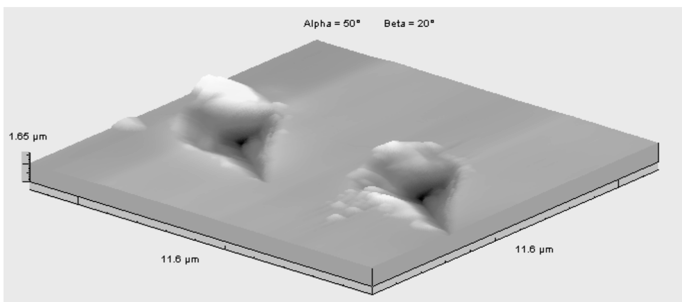


Figure 5: Indentation manipulation using an AFM probe: a wax surface is indented for making templates for nanofabrication [10].

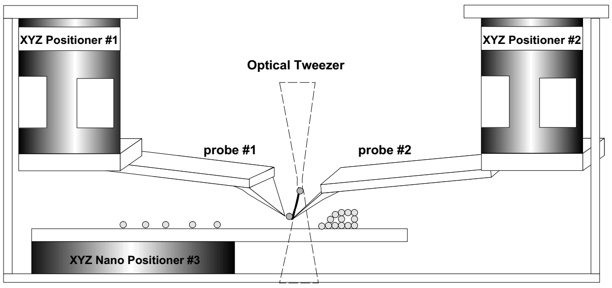


Figure 6: Integrated multiple AFM probes and optical tweezers setup design for 3D pick and place kind of complex nanomanipulation tasks [11].

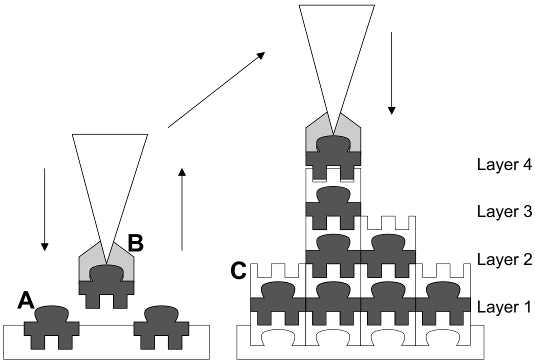


Figure 7: Chemical molecule deposition and recognition based pick-and-place scheme using one AFM probe (attraction force between the molecule B on the tip and molecule A must be smaller than the force between A and C).

cantilever deflection or vibration resonant frequency are changed due to the attractive or repulsive interatomic forces between the tip and sample atoms. Comparing these microscopes, STM has a better lateral resolution, i.e. STM probe interacts with less number of sample atoms, while AFM has a large interaction range. On the other hand, AFM has more application areas since it is applicable to any material while STM can be used only for conducting or semi-conducting materials. Furthermore, STM gives only 3D topology data, but AFM can provide both topology and interaction force data. This point is very advantageous in AFM for reliable force feedback from the nano world to the macro world [35].

AFM and STM are also utilized as a manipulator. However, at a given instant, they can be utilized only as a manipulation or imaging tool. Therefore, real-time 3D imaging is not possible at present in ambient or liquid environments during manipulation. For vacuum environments, Scanning Electron Microscope (SEM) as a far-field microscope [15], [16] is promising for observing the manipulator and nano object. Moreover, Optical Microscopy (OM) methods such as fluorescence microscopy can be used as a far-field sensor at nanometer resolution depending on the specific application.

4.2 Nano Force Sensing

Force sensing is very crucial at the nano scale since a real-time imaging tool is not available at present for ambient

Microscope Properties	AFM	STM	SEM	OM
Visible Object Sizes	> 0.1 nm	> 0.1 nm	> 5 nm	> 100 nm
Visible Object Type	all	conductors, 1/2conductors	conductors, 1/2conductors	all
Imaging Type	near-field	near-field	far-field	far-field
Interaction with Object	contact or non-contact	non-contact	non-contact	non-contact
Imaging Environment	all	vacuum or air	vacuum	air or liquid
Imaging Principle	interatomic forces	tunneling current	electron emission	light-matter interaction
Imaging Dimension	3-D	3-D	2-D	2-D

Figure 8: Main microscopes utilized for nanomanipulation, and their properties.

and liquid environments, and objects become fragile at the nano scale. AFM is widely utilized as a nano force sensor beside of its imaging and manipulation capabilities. In AFM, using optical detection system, normal and frictional forces can be measured in a coupled way [11]. A decoupled very high resolution 3D nano force sensing is challenging. Optical detection system needs a fixed laser beam and detector setup around the beam which makes the AFM setup head large and limited in motion. For compact and flexible manipulation systems, piezoresistive detection system (strain gauges at the nano scale) is a promising solution [24], [25], [26] since it is integrated to the AFM probe during the microfabrication process. However, piezoresistive detection has almost 10 times less resolution than the optical one due to the thermal and electrical noises.

5 Actuators

Nanomanipulator and/or the samples are actuated for positioning, orienting, or applying a load on the nano objects. Significant actuator design parameters are: accuracy, range of motion, degree of freedom (XYZ, $XYZ\theta\phi$, etc.), bandwidth (settling speed to a desired position) and linearity. Accuracy is determined by the actuator resolution, linearity, repeatability, and mechanical, electrical and thermal noises. For the desired accuracy, the rule of the thumb would be such that it should be at least 10-100 times smaller than the manipulated object size depending on the manipulation task precision requirement. For the range of motion, since the manipulated object is to be searched on the surface, 10-100 μm range fine motion actuator with an integrated cm range manual coarse stage is required. Bandwidth is important for especially industrial applications such as hard-disk storage. Linearity is adventageous since it enables open-loop control. However, most nanopositioners are nonlinear, and closed-loop control with integrated sensors are needed [25].

Main actuators at the nano scale are piezoelectric (PZT) tubes (most common) or tripods, PZT or ferroelectric thin-films, and microelectromechanical (MEMS) actuators such as electrostatic, thermal and capacitive ones. Furthermore, ultrasonic, elastomer, and Surface Acoustic Waves (SAW), etc. kind of novel actuators would also be useful. Moreover, besides of linear actuation, rotational motion is also needed for twisting type of manipulation tasks, and conventional high resolution motors are sufficient for long range rotation although its integration and alignment with the nanomanipulator motion space is difficult.

6 Nano Physics

As different from the macro scale, inertial forces become negligible going down to the nanometer scale. Moreover, continuum physics changes to molecular physics at the molecular scale. Researchers generally utilize approximate continuum models for the nano scale long-range and short-range forces [9]. On the other hand, using molecular dynamics or Monte Carlo simulations, molecular scale interactions are modeled more accurately [27]. The latter approach is important for detailed understanding of the nano scale phenomenon although it needs intensive computation. The former can give very close approximations for the molecular forces [28], and very fast to compute. Therefore, especially for real-time nano dynamics simulations and user interfaces and reliable nanogripper designs, continuum mechanics modeling would be sufficient. However, except simple geometric shapes such as sphere, plane, cone and cylinder, generic continuum models for van der Waals, capillary, contact deformation and electrostatic forces are needed to be developed.

Nanomanipulation dynamics consists of springs and dampers where attractive or repulsive external forces try to move objects. Adhesion is one of the main mechanisms that should be controlled for reliable and repeatable manipulation. In ambient conditions, capillary and electrostatic forces can dominate other forces, and pick-and-place kind of tasks are very challenging to realize. As one possible solution, manipulation can be realized in liquid [29] where both forces disappear although sample preparation and other forces become more complex. Since nano forces largely depend on the environmental parameters beside of material type and geometry, operation environment should be controlled for repeatable and precise adhesion control.

7 Control

For the control of the nanomanipulator, teleoperation or automatic manipulation approaches are utilized. In the former approach, a human operator directly in the control-loop manipulates the nano objects by using a man-machine user interface. Here, the operator controls the nanorobot directly or sends task commands to the nanorobot controller as shown in Figure 9. In the direct teleoperation system, the user interface consists of visual and force feedback devices. Hollis et al. [30] used tactile feedback from the nano world for the first time. In [31], [32], [33] and [11], force feedback and 3D real-time Virtual Reality graphics display interface are utilized during nanomanipulation. Direct teleoperation approach can realize tasks requiring high-level intelligence and flexibility. However, it is slow, not precise, not exactly repeatable, and engaged in many complex and challenging scale difference problems. On the other hand, the task-oriented approach avoids these problems by executing only the given tasks in a closed-loop autonomous control [24]. In the automatic control approach, nanorobot has a closed-loop control using sensory information without any user intervention. However, the automatic control in the nano world is not reliable at present due to the complexity of the nano dynamics, difficulties in accurate nano positioning and real-time visual feedback, changing and uncertain physical parameters, and insufficient models and intelligent strategies [34].

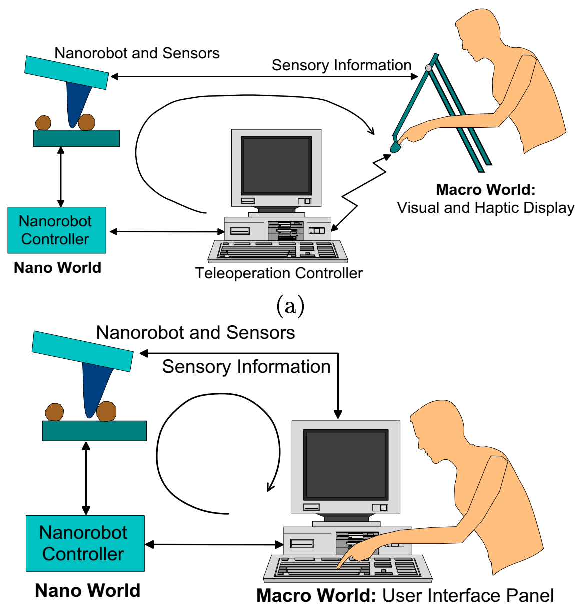


Figure 9: Teleoperation control approaches: (a) direct teleoperation; (b) task-oriented teleoperation.

8 Applications

Nanomanipulation systems enable to change, interact and control the nano scale phenomenon precisely. In the literature, these systems are used in many different applications:

- *Biotechnology:* Locally and precisely manipulating biological objects such as DNA [36], [37], [38], [39], [17], ribosome, proteins [19], etc. Beside of manipulation, same approach can be used for active measurement of twisting or bending compliance [40] of DNA. Automatic DNA sequencing by nanoprobes would have a revolutionary impact, but it has not been achieved yet. Moreover, by attaching biochemical enzymes to the tip of an AFM probe, mechanochemical manipulation of DNA is possible [41].

- *Computer Technology:* Hard disk storage is the main application for AFM probe based high density storage mechanisms. Heating the AFM tip or by mechanical indentation, bits can be written on polymer surfaces [42], [13]. Speed considerations are very crucial for this application for commercialization [43]. Therefore, some groups use array of probes parallelly for fast operation [44].
- *Micro/Nanotechnology:* Assembling nano scale objects would enable more complex machines with hybrid parts. Improving the nanoassembly technology, novel micro/nanofabrication techniques would become possible. Moreover, by local precision positioning of particles, nanotubes, or molecules, single-electron devices, quantum optics devices, etc. could be constructed or analyzed [45], [22].
- *Material Science:* For constructing novel materials and understanding the material properties at the nano scale, nano scale friction, adhesion, electrical properties, etc. should be understood. Actively manipulating materials on surfaces enable frictional and adhesional characterization of novel materials such as carbon nanotubes and nanoparticles. As a popular nanomanipulation material, many groups have been working on 2D and 3D bending, pushing and assembly of nanotubes [46], [47], [16], [48], [15]. Moreover, by indenting materials such as polymers, biological samples, etc., nano scale Young Modulus and hardness properties of materials are characterized quantitatively [49].

9 Conclusions

Nanomanipulation systems with their components are explained, and existing approaches and problems are reported. Moreover, some possible solutions are proposed. Summarizing the open nanomanipulation problems and future challenges:

- Fabricating a nanostructure with precision nanomanipulation would be slow for industrial applications even using array of manipulators. However, self-assembly kind of more parallel and natural processes would speed up the process and enable more complex 3D structures. Therefore, precision nanomanipulation and self-assembly should be integrated for future applications.
- Modeling nanoforces is essential for reliable manipulation, and analytical continuum models for electrostatic forces and liquid manipulation forces should be developed. Especially electrostatic forces are the most complex ones when the nano object or manipulator is a nonconducting material. Moreover, modeling of the nanotribology is crucial for on surface manipulation applications such as pushing nanoparticles [50].
- 3D nanoassembly is one of the most difficult challenges where novel nanogrippers or chemical manipulation techniques with proper nano physical and chemical modeling are needed to be developed.
- Real-time 3D nano scale imaging in air and liquid is not possible at present. New far-field microscopy techniques or replacing sensing methods are needed.
- Automatic and fast nanomanipulation is required for mass-production. Many open nonlinearity, uncertainty and disturbance problems are to be solved for stable and fast control.
- Novel multiple nanogripper designs with integrated sensors and actuators are needed for flexible and dexterous manipulation tasks. Microfabricated probes with PZT thin-film layers would be one solution.
- 3D uncoupled nano force sensing is desirable for 3D manipulation cases.
- Sample preparation is one of the most practical but crucial issues of nanomanipulation. Depositing semi-fixed nano objects on a substrate requires experience on adhesion, chemistry, nanotribology, and material science. For all specific applications and material types generic procedures should be introduced for manipulation standards.
- For teleoperated nano-manipulation, force scaling laws for reliable nano scale force feedback are to be defined analytically for a stable and transparent force-reflecting interaction.

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