Nanorobotic systems for nanomanipulation and nanopositioning

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Nanorobotics is currently a much studied field by the international scientific world. Numerous applications of nanorobotics make it to expand in several areas. This occurs through the integration of several disciplines, including nanofabrication processes used to produce nanorobots, nanoactuators, nano-sensors and nanometer scale physical modeling. Some of the most important applications of nanorobotics are nanopositioning and nanomanipulation. These, in turn, find many other applications to produce different MEMS/NEMS systems, in materials science, biomedical sciences, engineering sciences, etc.

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1. Introduction

On the nano scale basis, technology / micro-nanotechnology has shifted to a more powerful and intelligent control of material structure, suggesting the feasibility of achieving by the control of the molecular structure of matter atom by atom. Nanorobotics deals with the study of nanometer scale robotics and include robots that are nanometer-size and large robots able to manipulate objects with nanometer dimensions.

Nanorobotics [1] field integrates together various disciplines, including nanofabrication processes used to produce nanorobots, nanoactuators, nanosensors and nanometer scale physical modeling. Nanorobotics manipulation technologies, including nano-scale assembly of units, biological cells and molecules manipulation and types of robots used to perform these tasks also form a part of nanorobotics. With the ability to position and orient nanoscale objects, nanorobotic manipulation is a promising way to enable the assembly of nanosystems. Nanorobotic manipulation systems [2] can be used for nanoassembly, biotechnology, construction and characterization [3] of nanoelectromechanical systems (NEMS).

2. Manipulation methods

The most common ways to achieve nanometer scale setting in motion are the electrostatic, electromagnetic and piezoelectric. For nanorobotic manipulation besides nano-resolution and compact sizes, the actuators, generating large movements and forces, are the most suitable for such applications.

Speed criteria are less important as long as the speed of movement is in a few Hertz domain and more. Table 1 provides a small selection of researches regarding suitable actuators for the principle of movement in order to be used for nanorobotics applications.

Table 1. Actuation with MEMS.

Actuation principle	**Type of motion**	**Volume (mm^3)**	**Speed (s^{-1})**	**Force (N)**	**Stroke (m)**	**Resolution (m)**	**Power density (W/m^3)**
Electrostatic	Linear	400	5000	1×10^{-7}	6×10^{-6}	NA	200
Magnetic	Linear	0.4×0.4×0.5	1000	2.6×10^{-6}	1×10^{-4}	NA	3000
Piezoelectric	Linear	25.4×12.7×1.6	4000	350	1×10^{-3}	$7x10^{-8}$	NA
Thermal	Linear	0.3×0.3×0.4	2000	4.4×10^{-6}	2.5×10^{-6}	NA	NA
Actuation principle	**Type of motion**	**Volume (mm^3)**	**Speed (s^{-1})**	**Force (N)**	**Stroke (m)**	**Resolution (m)**	**Power density (W/m^3)**
Electrostatic	Rotational	$\pi/4\times0.5^2\times3$	40	2×10^{-7}	2π	NA	900
Magnetic	Rotational	2×3.7×0.5	150	1×10^{-6}	2π	$5/36\pi$	3000
Piezoelectric	Rotational	$\pi/4\times1.5^2\times0.5$	30	2×10^{-11}	0.7	NA	NA
Thermal	Rotational	$1\times1.5\times1.5^2$	70	1.6×10^{-6}	NA	NA	NA

Electrostatic charge is based on the accumulation of free electrons in a material, which can exert an attractive force on opposite charged objects or a repulsive force on similar charged objects. Because electrostatic fields appear and disappear quickly, such devices will have high operating speeds and will not be influenced by ambient temperature. Electrostatic fields can exert large forces, but generally across some very short distances. When the electric field should act on some long distances, it is necessary a greater potential to maintain given force. Very low power consumption associated with electrostatic devices determines moving highly efficient implementation.

Electromagnetic fields appear by the movement of electric current through a conductive material. Attractive or repulsive forces are generated adjacent to the conductor and proportional to current flow. It can be built structures which gather and focus electromagnetic forces and accumulate these forces to create movement. Electromagnetic fields appear and disappear quickly, allowing achievement of some devices with high operating speeds.

Piezoelectric movement appears after dimensional changes generated in certain crystalline materials subjected to an electric field or an electrical charge. In this way structures can be achieved, which collect and focus the force of dimensional changes and uses them to create movement. Thus, typical piezoelectric materials include SiO_2 and polymers, as polyvinyledene fluoride (PVDF). At the micro scale, piezoelectric materials were used in linear transport devices and most nanomanipulators use piezoelectric actuators.

Thermal movement produced by thermal expansion amplification. This refers to the tendency of matter to change in volume in response to a change in temperature.

3. Nanorobotic systems for nanomanipulation

Technologies /micro-nanotechnologies for nanomanipulation [4] include observation, setting in motion, measurement, system's design and manufacture, calibration and control, the results dissemination and man-machine interface. The basic requirements for a nanorobotic 3D system for nano-manipulation include nanometric scale positioning resolution, a large workspace, sufficient freedom degrees (including rotation for 3D positioning) and orientation's control of multiple effectors for complex operations. Currently nanomanipulation can be applied for scientific analysis of physical, biological phenomena and for prototype nanodevices building. It is a fundamental technology for characterizing nanomaterials, structures and mechanisms for nanodevices assembling as nanoelectromechanical systems (NEMS). Nanomanipulation was made possible by scanning tunneling microscopy (STM), the atomic force microscopes (AFM) and other types of microscopes appearance to scan the sample [5]. Nanorobotic manipulators (NRMs) have the 3D positioning capacity, orientation's control and systems employed in real-time observation that can be integrated with microscopes to scan the sample.

A comparison of STM, AFM and NMRs technologies is shown in Fig. 1.

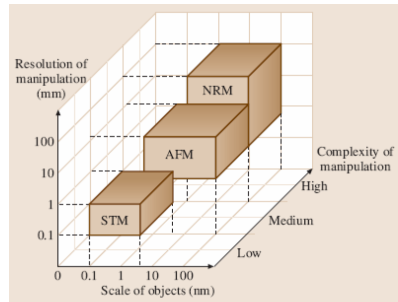


Fig. 1. Comparison of nanomanipulators.

STM can be applied to particles with the size of atoms. A standard STM is not suitable for complex manipulation and cannot be used in 3D space because of its limitation in 2D positioning.

In the case of AFM, there are three picture modes, respectively the contact, the binding mode (regular contact mode) and non-contact mode. The last two are so-called dynamic modules and can achieve a higher resolution than the contact mode. Atomic resolution is achievable with non-contact mode. Manipulation can be done with an AFM in contact or dynamic mode. Generally, AFM manipulation involves the movement of an object by tapping it with a spike. A typical manipulation occurs as follows: the image of a particle in non-contact mode, then oscillations remove and the sweep of the peak over the particle that is in contact with the surface. The mechanical pushing can exert more powerful forces on objects and so, it can be applied to manipulate larger objects. 1D and 3D objects can be manipulated on a 2D substrate.

A commercially available nanomanipulator (MM3A from Kleindiek) installed inside an SEM (Carl Zeiss DSM962) is presented in Fig. 2. The manipulator has three degrees of freedom and nanometeric scale resolution at sub-nanometric scale (Table 2).

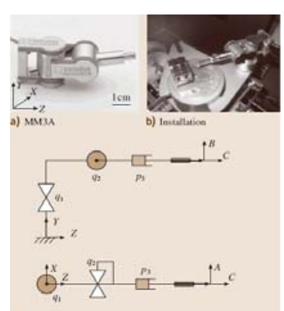


Fig. 2. Nanomanipulator (MM3A from Kleindiek) inside a SEM.

Table 2. Specifications of MM3A.

Item	Specification
Operating range q_1 and q_2	240°
Operating range Z	12 mm
Resolution A (horizonal)	10^{-7} rad (5 nm)
Resolution B (verical)	10^{-7} rad (3.5 nm)
Resolution C (linear)	0.25 nm
Fine (scan) range A	20 µm
Fine (scan) range B	15 µm
Fine (scan) range C	1 µm
Speed A, B	10 mm/s
Speed C	2 mm/s

Calculations show that, when scanning in the A / B direction by q_1/q_2 connection, additional linear motion in C is very small.

A nanorobotic manipulation system with 16 degrees of freedom (DOFs) is shown in Fig. 3a, which can be equipped with three or four AFM peaks as effectors both for manipulation and measurement. System specifications are presented in Table 3. Functions of nanorobotic manipulation system for nanomanipulation, nanoinstrumentation, nano-fabrication and nanoassembly are presented in Table 4. Measurements of four semiconductor samples are probably the most complex manipulation that can perform this system because it is necessary to stimulate four independent samples by four manipulators. Thus, three manipulators can be used to assemble a nanotube transistor, a third sample can be applied to cut a tube placed on other two samples, four samples can be used for measurements with four-terminals to characterize the electrical properties of a nanotube or a junction with nanotube. If all four samples are used together, many and various applications are possible for manipulators.

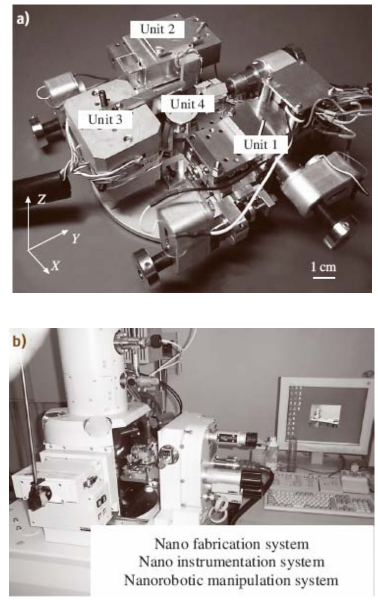


Fig. 3. a, b. Nanorobotic system. (a) Nanorobotic manip-ulators. (b) System set-up.

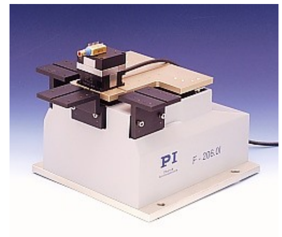
Table 3. Specifications of nanorobotic nanomanipulation system.

Item	Specification
Nanorobotic manipulation system	
DOFs	Total: 16 DOFs
	Unit 1: 3 DOFs (x, y and β; coarse)
	Unit 2: 1 DOF (z, coarse), 3-DOF (x, y and z; fine)
	Unit 3: 6 DOFs (x, y, z, α, β, γ; ultrafine)
Actuators	4 Picomotors (Units 1&2)
	9 PZTs (Units 2&3)
	7 Nanomotors (Units 2&4)
End-effectors	3 AFM cantilevers + 1 substrate or 4 AFM cantilevers
Working space	18 mm × 18 mm × 12 mm × 360° (coarse, fine), 26 µm × 22 µm × 35 µm (ultrafine)
Positioning resolution	30 nm (coarse), 2mrad (coarse), 2 nm (fine), sub-nm (ultrafine)
Sensing system	FESEM (imaging resolution: nm) and AFM cantilevers
Nanoinstrumentation system	
FESEM	Imaging resolution: 1.5 nm
AFM cantilever	Stiffness constant: 0.03 nN/nm
Nanofabrication system	
EBID	FESEM emitter: T-FE
	CNT emitter

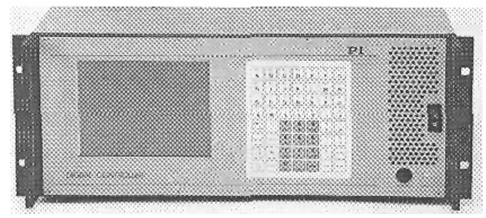
A nano laboratory is shown in Fig. 3b and its specifications are in Table 3. The nano laboratory integrates a nanorobotic system for nanomanipulation with an analytical system and a nanofabrication system. It can be applied for nanomaterials manipulation, nano-groups manufacturing, nanodevices assembling and in situ properties analysis of such materials, groups and devices.

Table 4. Functions of a nanorobotic nanomanipulation system.

Functions	Manipulations involved
Nanomanipulation	Picking up nanotubes by controlling intermolecular and surface forces, and positioning them together in 3-D space
Nanoinstrumentation	Mechanical properties: building and stretching
	Electrical properties: placing between two probes (electrodes)
Nanofabrication	EBID with a CNT emitter and parallel EBID
	Destructive fabrication: breaking
	Shape modification: deforming by bending and buckling and fixing with EBID
Nanoassembly	Connecting with van der Waals
	Soldering with EBID
	Bonding through mechano-chemical synthesis



a) Hexapod positioning system – all commands and operations are using (X,Y,Z and U,V,W) coordinates. Travel range: X = -8 to +5.7 mm, Y = ±5.7 mm, Z = ±6.7 mm, U = ±5.7°, V = ±6.6°, W = ±5.5°.



(a) Control unit

Fig. 4. F-206 alignment and positioning system with six axes: hexapod positioning system (a) and control unit (b).

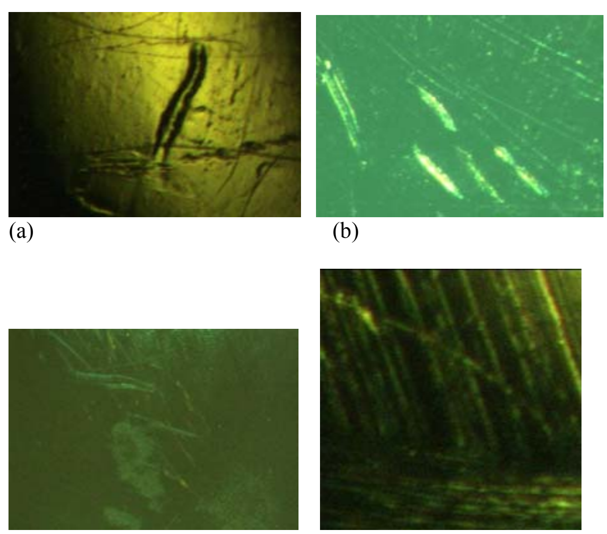
4. Technology of incdmtm

By separating the image making and manipulating functions, nanorobotic nanomanipulators may have more degrees of freedom including rotation for control of orientation and thus, can be used to manipulate 0D objects (spherically symmetric) to 3D objects in space.

A Hexapod positioning system for Micro-Movement F-206 (Fig. 4), produced by Physics Instruments (PI) GmbH & Co [6]. KG, Karlsruhe, Germany is integrated at INCDMTM, within MEMS / NEMS laboratory. 6-axis positioning system F-206 consists of an attachment position device and a control unit. A keyboard and a monitor for the control unit (either included or connected as a peripheral device) may be used to control F-206 system directly or, typically, the control unit can be controlled by a PC. System's mechanics uses a parallel - cinematic positioning system. The mechanical system contains 6 linear actuators with screw actuators and optical encryption systems. The system provides 6 degrees of freedom and a minimal increase of movement of 0.1 µm. Workspace boundaries are not parallel to the axes, but they cannot overcome a rectangular solid which is given by the limits of movement X, Y and Z. The control unit is equipped with integrated software to define a pivot point anywhere inside or outside workspace of F-206 system. Rotation around this pivot point may be ordered for any combination of the 3 rotation axes. Digital command system processes complex positioning and elements of movement, including scanning procedures and alignments using optical or analog response signals from more than 2 meters.

All orders for "F-206 platform" positioning are given in orthogonal coordinates and converted by command system in F-206 specific actuator positions and speeds before making the action.

This system is currently used for positioning the samples studied with an atomic force microscope [7]. The connection between these two systems is done with a finger device that allows nanopositioning of samples used. Results obtained with this device are presented in Fig. 5.



(a) (b) (c) (d)

Fig. 5. Images obtained with the device Hexapod system for Micro - Movement F-206 - AFM. Images of cutting (a), scratches (b, d) and particle (c) on Co-Cr femoral head of a hip prosthesis (*MEMS*/*NEMS Laboratory*, *INCDMTM*).

5. Nanomanipulation and nanopositioning applications

One of the most important applications of nanorobotic nanomanipulation is nanorobotic assembly. Self-assembly is required when starting from atoms; groups of molecules can self-assemble rapidly because of their thermal motion, allowing them to explore the environment and finding complementary molecules.

Nanorobotics provides new techniques for exploring the bio field by manipulation and characterization of nanoscopic objects as cell membranes, DNA and other biomolecules [8]. Materials science, biotechnology, electronics and mechanical stimulation will benefit from nanorobotics developments [9]. Research topics in biorobotics include autonomous manipulation of cells or molecules, characterization of mechanical properties of biomembranes tuning nanorobotic systems with integrated vision and force sensing modules. The objective is to obtain a fundamental understanding of uni-cellular biological systems and studies of wrong cells. Because of their important role, proteins are candidates for work in artificial self-assembled molecular systems.

Nanorobotic manipulation serves as the basis for building nanodevices by structuring materials to obtain groups and assembling them in more complex systems. Robotic manipulation at nanometric scale is a promising technology to design, characterize and assembly nano-groups to produce NEMS.

Nanoinstruments, sensors and actuators can provide measurements and /or movements which are calculated in nanometers, gigahertz, piconewtons, femtograms, etc. Efforts are focused on developing technologies for carbon nanotubes [10] and other nanomaterials and NEMS structures.

6. Conclusions

INCDMTM Bucharest, Romania, by its MEMS/NEMS Laboratory, will develop in the future, micro/nanorobotic systems/ micro-nanosystems for micro/ nanomanipulation and micro/ nanopositioning, micro/ nanotechnological micro/ nanoplatforms for European modernization and qualifications of micro/ nanoindustries and micro/ nanoengineering.

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