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A nanomanipulation platform for semi automated manipulation of nano-sized objects using mobile microrobots inside a Scanning Electron Microscope

**C.Canales*. F.Kaegi* . C.Groux* . JM. Breguet*.
C.Meyer** . U.Zbinden ** . A.Steinecker****

*Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratoire des Systèmes Robotiques (LSRO), Ecublens, CH-1015 Switzerland (Tel: ++41216937833; e-mail: christophe.canales@epfl.ch).
**Centre Suisse D'Electronique et de Microtechnique (CSEM), Untere Gründlistrasse 1, Alpnach, CH-6055, Switzerland (e-mail:celine.meyer@csem.ch)

Abstract: In the scope of the NanoHand project, a compact and versatile nanomanipulation platform is being developed. This platform is aimed to manipulate and characterize nano-sized objects using the vision feedback from a Scanning Electron Microscope (SEM). The platform is composed of mobile microrobots with four degrees of freedom (X,Y,Z,θz) located on a cartesian XY stage. Thanks to its compactness, the complete platform can be loaded through the exchange bay of a SEM. Final application is the manipulation and characterization of CNTs (Carbon Nanotubes) and nanowires.

1. INTRODUCTION

The objective of the EU project NanoHand (micro-nano system for automatic handling of nano-objects) is to develop systems for handling and characterization of nanoscale objects. The short term objective of the project is to have demonstrators able to decorate Atomic Force Microscope (AFM) tips with Multi Walled Carbon Nanotubes (MWCNTs) in a semi automated way (up to ten tips per hour). The long term objective is to study the suitability of Single Walled Carbon Nanotubes (SWCNTs) in nanoelectronics.

Different demonstrators will be developed by the members of the NanoHand consortium.
One of them, called the "NanoFab" will be developed by Klocke Nanotechnik and will be designed for a specific task (decoration of AFM tips with CNTs) for industrial products.
The other, which is the one presented in this paper, is called the "NanoLab". It aims to be a flexible manipulation platform based on both mobile and stationary robots, and is intended for handling and characterization of nano-objects.

In the NanoLab, mobile microrobots have been preferred over stationary manipulators for their compactness, ease of use and flexibility. Mobile robots can easily be adapted to various configurations and used for a wide range of applications [Driesen 05]. They do not require adding specific fixation holes in the system, and they provide a nanmometric resolution over a range of several tenths of millimetres.

The NanoLab platform is semi automated. This means that only a subset of the tasks necessary for a nanomanipulation experiment are fully automated. The others still require a user to manually control the different platform elements. However, all user-controlled operations are assisted by the platform software, simplifying the manipulation, as it is explained in the section 6 (automation).

2. PLATFORM CONCEPT AND CAPABILITIES

2.1 Overview of the NanoLab

The whole NanoLab is divided in two subsystems (see Figure 1). The reason for this division is explained in the section 2.2.

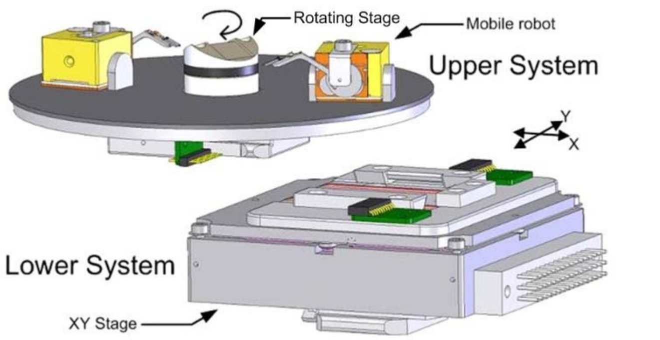

Figure 1 The two subsystems composing the NanoLab

The lower part of the NanoLab consists in a high precision XY stage which will be fixed on the SEM Stage using the SEM sample holder.

The upper part of the NanoLab is composed of a circular plate where the mobile microrobots and a rotating stage are placed. The samples to manipulate will be fixed on the rotating stage and nanomanipulation tools (grippers, probes…) will be carried by the mobile microrobots.

The stage of the lower system will permit to move the whole upper system (robots, rotating stage and sample) in both X and Y. Thanks to its kinematics, the Nanolab permits to scan a large sample area (10x10mm^2) even when the field of view of the observation system is limited.

The concept of a complete manipulation and characterization platform working in a SEM has already been presented as Lab in SEM [Breguet 04]. Moreover, numerous manipulators based on the stick-slip principle have already been fabricated by the EPFL-LSRO group and successfully tested for a wide range of manipulations inside a SEM [Rabe]

2.2 Loading of the NanoLab

A major part of the time required to set-up an experiment is taken by placing, fixing and connecting the manipulators. Another non negligible time is taken by reaching a high level of vacuum (typically 1.3x10-3 Pa) in the vacuum chamber of the SEM after the sample loading.

To reduce this time, numerous SEM manufacturers have developed an "exchange bay". This system permits to load the samples through a narrow bay rather than by opening the whole chamber. Thanks to this, a high vacuum level can be reached in a few minutes after the sample loading.

In the NanoHand project, the NanoLab platform will operate in a Hitachi S-4800 SEM (see Figure 2), which is equipped of an exchange bay with a size of 130x34mm^2.

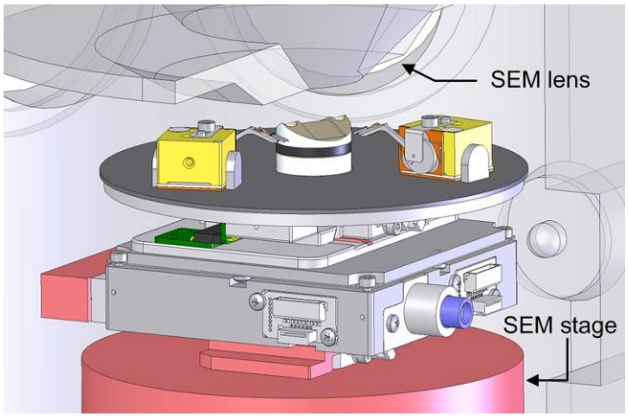

Figure 2 NanoLab in the Hitachi S-4800 chamber

Even if the components of the platform have been designed to be especially compact, the size of the whole system makes a single loading through the exchange bay impossible.

For this reason, the NanoLab has been divided in two subsystems, which are successively loaded in the SEM chamber.

The lower subsystem is loaded first. The SEM stage is then lowered to make room for the upper subsystem which will be connected to the first element. The complete platform is mechanically fixed to the SEM stage by means of flexure hinges, and electrically connected thanks to a connector located behind the XY stage of the lower system.

2.3 NanoLab actuation

All the elements of the NanoLab platform are driven by piezo actuators working either in stick-slip or scanning mode.

The stick-slip mode consists in a slow deformation of a moving "foot" in one direction (stick) that will be followed by a sudden return in the opposite direction (slip) [Breguet 98]. The step of the actuator, which defines the resolution in stick-slip mode, is typically around 300 nm with the EPFL manipulators.

A sub-step resolution can be achieved by driving the actuators with a constant voltage (also called scanning mode). In scanning mode, the displacement resolution of the actuators is only limited by the noise of the driving signal.

The actuation signal for the stick slip mode is a saw tooth generated by a compact voltage amplifier designed within the LSRO group at the EPFL. This electronic is capable of generating a 400Vpp signal with a frequency up to 25 kHz and a high slew-rate (400 V/µsec). In addition to the scanning mode, the EPFL amplifier can provide a constant voltage to also drive the manipulators in scanning mode.

In order to reduce the number of signal generators required for the platform and to facilitate the implementation of the control software, all the manipulators (stages and mobile robots) are actuated using the same type of signals (saw tooth for stick-slip or constant voltage for scanning).

3. XY STAGE

3.1 Overview of existing stages and motivation for the development of a custom system

Developing a custom stage for the NanoLab was the solution to get the best trade-off between compactness, high precision and high displacement range

Numerous manufacturers provide XY stages compatible for a use in SEM, for example Klocke Nanotechnik, SmarAct, Physik Instrumente and Kleindiek.
Stages using stack actuators with flexures hinges offer a good resolution but have a limited travelling range (less than 100 µm).
Stages using stepping principles permit to have a higher displacement range (a few tenth of mm), but are generally larger and are rarely equipped with position sensors.

3.2 Design and fabrication

The stage is composed of two mobile plates in a serial configuration. Piezo actuators in shear modes from PI are used in stick-slip mode to drive the two mobile plates. Guiding is realized using stainless steel shafts sliding over V-shaped sapphire elements glued on top of the piezos.

Two compact linear encoders from Numerik-Jena are used as position sensors. These encoders have a resolution of 50nm after a 100x interpolation of the encoder output signal.

3.3 SEM and TEM compatibility

The thrust force of the piezo actuator is significantly increased when a high normal force (called preload) is applied between the fix and mobile part [Mazerolles]. Conventionally, this force is created using magnets. However, magnets located too close from the electron beam of the SEM could disturb the electrons and thus blur the image of the sample. Shielding of the magnets could be a solution to prevent this phenomenon, but it would increase the complexity of the system.
To avoid magnetic perturbations, in the XY stage developed for NanoHand, the preload is realized using flexible springs

elements rather than magnets. The interface between the spring elements and the mobile plate of the stage is realized by means of three stainless steel balls rolling between the fixed and mobile plate (see Figure 3). To ensure a good resolution of stage, it is crucial that the steal balls always roll and not slide.

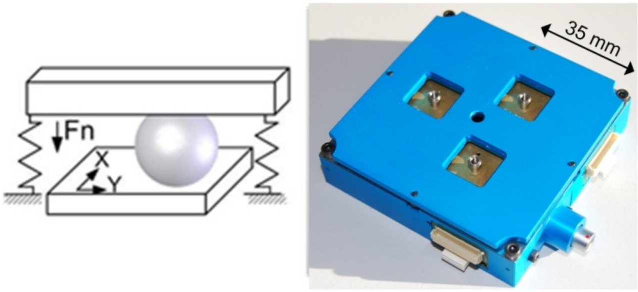

Figure 3 Preload system and picture of the XY Stage

In scanning mode, the Hitachi S-4800 can provide a picture with a resolution of 3 nm. When used in Transmission mode, pictures with a resolution up to 1nm at 15kV can be obtained. Nevertheless for TEM observation, the sample has to be cut in a thin lamella (between 20 to 70 microns). In the transmission mode, the electron beam has to go through the sample and is collected by a sensor located below the complete platform. For this reason, the XY stage has been designed with a hole in its centre.

3.4 Specifications and performances

The characteristics of the XY Stage are the following:

- Overall size: $69x69x18.5mm^3$
- Travelling range: 10x10 mm^2
- Travelling speed: up to 8 mm/sec at 22 kHz
- Displacement resolution for X and Y: < 3 nm (in scanning mode)
- Positioning repeatability for X and Y: < 500 nm (using the stage optical encoders to close the loop)

The Figure 4 represents the travelling speed of the stage for various amplitudes and frequencies of the saw tooth signal.

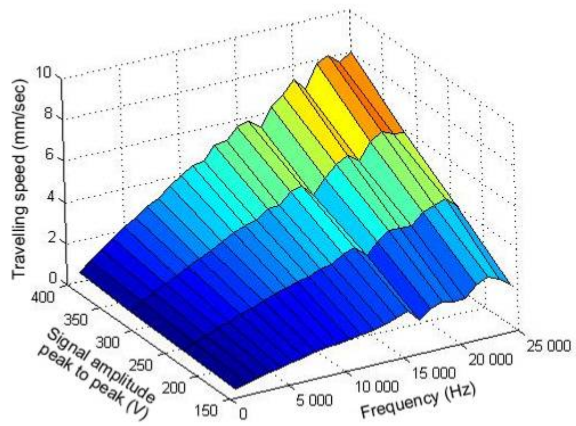

Figure 4 Travelling speed of the stage in X

4. MOBILE MICROROBOTS

4.1 Overview of the EPFL microrobots

Microrobots developed in the scope of the NanoHand project have the objective to provide robust and easy to use manipulators, offering a nanometric resolution. Several research groups have developed mobile microrobots [Woern] with a nanometric resolution. Nevertheless, most of these robots require a complex assembly of small sized components or costly microfabrication processes in clean room.

Thanks to their limited number of components and their simple Monolithic Push-pull actuators (MPA), the EPFL microrobots are a robust and compact solution for tasks ranging from micro to nanomanipulation [Driesen 05, Robio]. The MPA actuators used in the mobile microrobots can be produced cost efficiently (even in small batches) in a standard environment using thick film lithography.

The mobile microrobots are composed of a brass body on which two MPAs are fixed. Brass has been chosen in order to increase the robot weight, providing a higher normal force and more inertia to the robot. The first actuator called Planar MPA (see subsection 4.2) could be described as the feet of the robot.

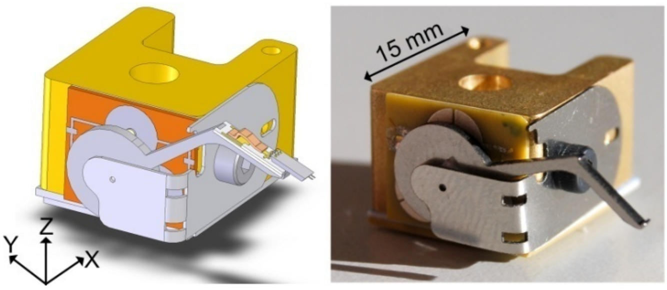

Figure 5 Mobile Microrobot

4.2 Planar MPA actuator

Monolithic Push-pull Actuators (MPA) have been developed at EPFL. Planar MPA is used as a locomotion platform for the mobile robots, offering three degrees of freedom in a compact and affordable module. These actuators are based on the push-pull principle to move the body of the robot over a substrate [Bergander].

The planar actuator is composed of three sets of electrodes patterned on a piezo-plate. On one side of the piezo-plate, each set is subdivided in four smaller electrodes. On the other side, all the sets are linked and will be grounded. By applying a high voltage to specific electrodes of a set, the centre of the set can translate along two perpendicular axes. By combining the effects of the three sets, the robot can translate in X, Y and rotate in θz (see referential in Figure 5).

The tripod actuator has been designed in three different sizes

- Compact version: 12x13.5 mm^2
- Standard version: 15x15 mm^2 (see Figure 6)

- Larger version: 18.5x20 mm^2

Figure 6 Planar MPA frontside (left) and backside (right)

In every configuration, four high voltage signals and one ground are required to drive the robot.

4.3 Rotary MPA actuator

The arm of the robot is driven by a rotary MPA actuator, which enable it to rotate around θ_Y (see Figure 5)

The rotary MPA actuator is based on the same push-pull principle than the planar MPA actuator. The difference between the two types of actuators is the shape of the electrodes. Each set of electrodes of the rotary actuator are divided in two subsections instead of four. In this configuration, the centre of each set will move along a direction tangential to a circle passing through the centres of the three sets.

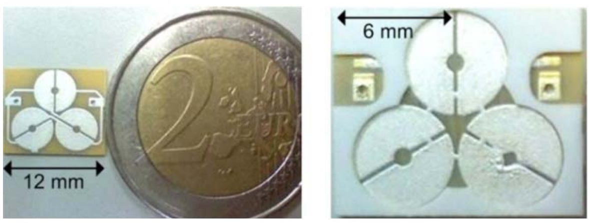

Figure 7 Rotary MPA frontside (left) and backside (right)

Only two high voltage channels and one ground are required to drive the actuator.

The rotary MPA actuator has an overall size of 10x12x0.75mm^2 (see Figure 7)

4.4 Robot actuation and wiring

As for the XY stage, the robots are actuated using the stick slip principle for a coarse positioning. The fine positioning is ensured by actuating the MPA in scanning mode (constant voltage applied to the electrodes of the piezo-plate).

Completely autonomous microrobots are a long term objective for the LSRO. Nevertheless the priority for the NanoHand project is more focused towards reliability than autonomy. On-board electronics could cause various heating problems when used in vacuum (no heat diffusion by convection).
With off-board electronics, the major problem to face is the wiring of the robots. As the size of the robot decreases, the wires, by their stiffness, will influence the motion of the robot.

Due to its high flexibility, the most suited cable for connecting the mobile robots is the microminiature flat cable from GORE™. With a pitch of 100 µm this cable can provide up to 20 wires and withstand a use of the robot in vacuum. The gore cable is connected to the robot actuator by gold wire bonding.

4.5 Tools integration

As a partner of the NanoHand project, the MIC (Institute for Micro and Nanotechnology) within the DTU (Technical University of Denmark) has developed a microgripper for the handling of CNTs and nanowires. This gripper is composed of two sets of three free standing silicon beams on a 1.5x3.5 mm^2 silicon chip. Electro-thermal actuation is used to open and close the gripper. [Mølhave]

To easily connect and disconnect the MIC gripper on the microrobot arm, a special interface has been created. The mounting interface provides the mechanical fixation and three electrical connections. Mechanical fixation is realized by means of a spring element in Copper Beryllium pressing the silicon chip against a substrate fixed on the robot arm. Copper Beryllium being conductive, the spring element also provides one electrical connection to the silicon chip. The two other electrical connections are provided using conductive bumps contacting the fixed PCB to the chip substrate.

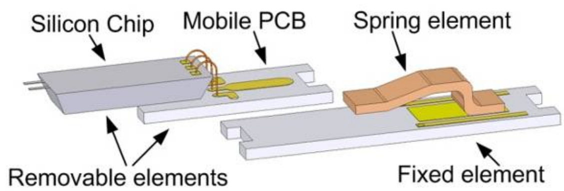

Figure 8 Tool interface

The tool interface has been designed for the MIC gripper, but virtually, any microtool (AFM tip, electrical probe…) located on a silicon chip and requiring up to three electrical connections could be mounted instead of the gripper

5. ROBOT CONTROL STRATEGY

5.1 Overview

As the mobile robots are sensorless, an external position measurement is necessary for closed-loop control. Position feedback is given by vision, using two different and complementary sensors. One gives a global view of the whole setup, allowing the coarse positioning of the robots. The second shows a high resolution view of the tool carried by the robot at a much higher magnification, allowing the fine control of the manipulations.
It is then possible to navigate the robots autonomously to a position where the tool can be seen in the local view, using the global view to track the robot. Then, the fine manipulation is performed with the help of the local view information.

5.2 Hardware

In a SEM, the local view (high magnification) is provided by the SEM itself. A camera for the global view must then be included in the chamber for the coarse manipulation.
Some nanomanipulation tasks can also be achieved under standard light microscopy. Indeed, even if the wave length of visible light is not short enough to properly see nanoelements, large nanowires (50 nm diameter) can still cause diffractions, enabling the user to "see" them [Boggild]. Thus, a first setup was installed under a conventional light microscope to demonstrate the control principle of the NanoLab.

The hardware for both in and off-SEM demonstrators is almost identical. The only difference comes from the use of a light microscope instead of the electron beam for the local view. (See detailed characteristics in Table 1).

	Global View	Local View Off-SEM		Local View In-SEM
		Lowest magn.	Highest magn.	
Camera / Frame Grabber	IDS µEye UI 1480-C	IDS µEye UI 1460-C		Matrox Morphis
Sensor	CMOS 1/2" 2560 by 1920 pixels	CMOS 1/2" 2048 by 1536 pixels		Hitachi S-4800 1280 by 960 pixels
Optics	17mm focal length			
Field of View	Variable according to working distance	456 by 342 µm	72 by 54 µm	Variable according to working distance and magnification
Resolu-tion (theory)	Dependent on field of view*	223 nm/pixel	35 nm/pixel	Dependent on field of view**

*for a field of view of 35x40 mm^2, resolution of about 17 um/pixel.
**for a working distance of 3 mm, with the minimal magnification, field of view of 3.6x3.6 mm^2, resolution of about 3.75 um/pixel, with the maximal magnification, field of view of 157x157nm^2, resolution of about 0.16 nm/pixel

Table 1 Hardware characteristics

Regarding the physical implementation, the in-SEM configuration causes a certain number of additional difficulties due to the particular SEM chamber environment. The global view camera has to work in the infra-red domain, as conventional illumination would damage the SEM sensor. It must be cooled by a mechanical connection to the outside to balance for the lack of heat convection in vacuum. Finally its components must be able to keep up with vacuum without outgasing. However, it has already been proven that some basic off-the-shelf CCDs meet all those conditions. [Fatikow]

From the control point of view, the only difference comes from the image acquisition, realized in both cases by third party components and software.
As for now, only the off-SEM setup was completely built and tested, thus this paper will mainly focus on this implementation.

5.4 Control software overview

Several members of the NanoHand consortium work on different aspects and versions of the NanoLab demonstrator. All software approaches are based on the same modular structure as seen in figure 6.

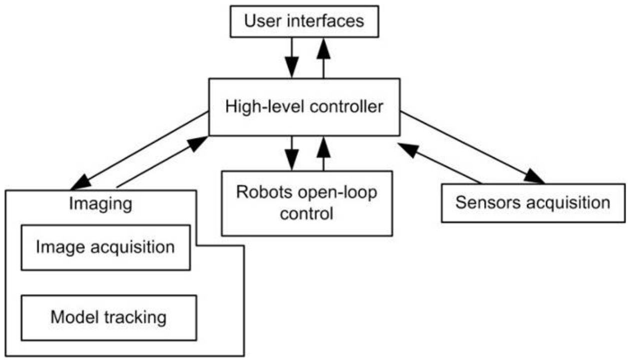

Figure 9 Software architecture

The low-level modules do not interact. They process "blindly" their data according to the high-level controller commands. They are responsible for initialization and parameters settings, as well as low-level tasks.
The high-level controller uses their various inputs to close the automation loops and executes the user commands.
Communication interfaces are common to all implementations of the control software. It is then possible to exchange modules or submodules between partners and to quickly adapt to different setup configurations or new hardware.

5.5 Details on imaging

The image acquisition classes are mainly interfaces to the third party software of the imaging devices. For the SEM, this can be either the proprietary SEM software or the cross-platform DISS 5 package from Point Electronics.
The model tracking submodule defines and then identify models in those images, in order to compute the position and orientation of the tracked objects. In our implementation, different image processing strategies are used.
For the tracking of the mobile robots in the global view, each robot has a unique pattern made of two circles on its upper surface, to identify it. This pattern is extracted via a quick blob analysis of the image, giving the robot position and orientation.
In the local view, the different objects are identified based on edges detection or pattern matching (grey levels correlation).
All image processing algorithms were implemented using the Matrox Imaging Library software.

5.6 Processing considerations

Both the SEM and the CMOS cameras allow grabbing only the pixels of an area of interest (AOI). This reduces the acquisition and processing time. As an example, in full frame mode, the global view CMOS camera can grab up to 6 frames per second. With an area of interest of 320x240 pixels, the frames rate can reach up to 126 frames per seconds.
With the SEM, the grabbing frame rate is much lower, sometimes only 2 images of usable quality per second, even when using a small AOI. This is mainly due to the technique of averaging several frames to reduce the noise.
It is then clear that the imaging bottleneck (and thus the main limitation for real time control) is the image acquisition and not the data processing.

6. AUTOMATION

The NanoLab is designed for lab-scale manipulations, where, each experiment requires a new setup and a different approach, making a full automation only possible on a case–by-case basis. However, it is possible to automate some subprocesses that take place in almost any manipulation.

6.1 Autonomous navigation in local view

The most time consuming part of any nanomanipulation is the preparation of the experiment: installing all the components, getting an image of good quality and bringing both samples and tools in focus in the field of view without collisions. Thus, we chose to automate this last step by implementing the autonomous navigation of the robot from its parking position to the local view (tool visible in the high magnification image). The reverse autonomous drive to a safe parking position is of course also possible.
Both trajectories implement path planning with obstacle avoidance based on intermediate goals.

6.2 Transparent tool manipulation

The use of non guided mobile robots implies some distortion between the commands sent by an operator and the resulting movement of the device. A user is also typically interested in controlling the tool itself, not the mobile robot.
We implemented the background process that allows the user to consider that he is controlling the tool carried by the robot in the natural reference frame corresponding to the image he sees on screen. He does not need to care about the actual robot behind the end effector and its limitations. A background process uses the tracked positions and orientations of the robot to make the necessary reference frame transformations and controls the robot in closed-loop according to the user's commands.

7. CONCLUSION

A nanomanipulation platform has been presented, with an overview of its different manipulators and control strategy.

The complete platform has already been successfully tested under a light microscope. Moreover, specific components such as microrobot and XY stage have independently been tested inside a SEM.

The next task of the project will be the integration of the whole platform inside a SEM, in order to perform a concrete nanomanipulation experiment.

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