SIXTH FRAMEWORK PROGRAMME
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NANORAC – STRP 013680

Publishable Executive Summary
(of the Periodic Activity Report)

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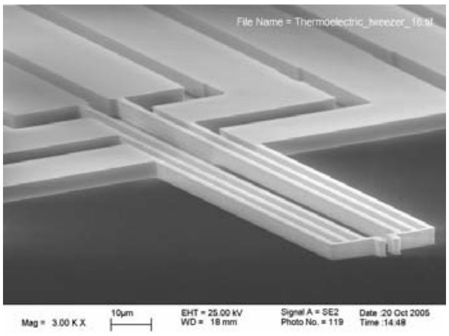
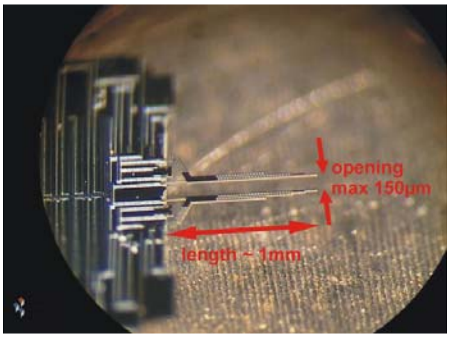
Publishable executive summary

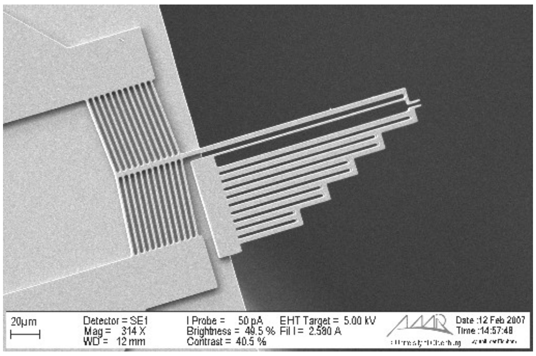
NANORAC (Nano-robotics for assembly characterisation) is a 3 year STREP project that tackles the characterisation and manipulation of nano-objects by developing a robotic system suited to untrained operators. The concept is applicable to all kinds of nano-scale objects, but focuses on carbon nanotubes (CNTs). Its essential goal is to perform characterisation (of the nano-object geometrical, mechanical and electrical properties), sorting and assembly tasks. These are basically pick-up and release tasks. The project has started on 1st May 2005 with 6 partners: CEA-List (F) as coordinator, University of Oldenburg (D), University of Cambridge (UK), Denmark Technical University (DK), Paris VI University (F) and Nascatec, a German SME. The EC support amounts to 1 350 000 €.



SEM image of a prototype NANORAC 3 beam nano-gripper (MIC, DK)



Prototype NANORAC micro-gripper (Nascatec, D)



View of an alternative asymmetric gripper (MIC, DK)

The difficulties of handling nano-objects result first from the domination of intermolecular and adhesion forces over inertial forces at nano-scale. In particular, adhesion and electro-static forces are not well mastered because their effect is driven by the geometry of the involved objects (that is often only approximately known) and by the distribution of the electrical charges (that is most of the time completely unknown). Additionally, these forces are highly dependant on the environment conditions (temperature, humidity, vacuum …). The dynamic behaviour of the simplest nano-objects thus becomes unpredictable and elementary manipulation tasks (grasping and especially releasing) are difficult to perform. Perception is the second main barrier limiting nano-manipulation. The drastic difference between the nano- and the micro-worlds is the lack of direct imaging. Viewing small nano-objects is only possible through non-optical tools like the Scanning Electron Microscope (SEM), which:

- provides 2D images (insufficient for accurate positioning)
- constitutes a "real-time" technique compatible with simultaneous manipulation
- operates on conducting objects inside a controlled environment (vacuum),

and the Atomic Force Microscope (AFM) allowing 3D perception, albeit with scanning delays and a definitive impossibility of performing at the same time sensing and manipulation.

In this context, NANORAC has defined four sub-goals:

- Simulation: understand, model and, as far as "usefully" possible, reproduce the dynamic behaviour of nano-scale objects in their environment
- Manipulation: develop devices and control strategies for manipulating nano-scale objects
- Human interaction: provide the human with the feedback and assistance to surpass the unfamiliarity of nano-scale manipulation
- Validation: global assessment of the developed hardware and software tools with respect to representative nano-manipulation tasks.

Regarding dynamic simulation, the project aims at providing a realistic Virtual Reality (VR) environment able (i) to enhance the human manipulation skill at nano-scale (this is the main goal), (ii) to assist in the design of manipulation devices and control strategies and (iii) to help understanding the nano-scale dynamic phenomena. A VR application featuring an interactive dynamic simulator suited to the nano-world is thus developed. It is necessarily based on the understanding and quantification of physical phenomena at nano-scale (nanophysics). It must also exploit 3D perception data provided by an SEM imaging and geometric data extraction module.

The work on manipulation techniques also benefits from nanophysics investigations. Its objectives are twofold:

- Design, production and test of both a nano-gripper dedicated to the handling of sub-micron objects (10 nm – 1 µm) and a micro-gripper for super-micron objects (100 nm – 10 µm)
  It is worth mentioning here the coating of grippers with CNT films as an anti-stiction feature and the integration of CNTs on the end-effectors to better adapt them to the requirements of the tasks.
- Develop manipulation strategies and control
  This work is based on simulations of pick-up and release tasks relying on an analytical model of gripping. It aims at implementing manipulation strategies appropriate to nanophysics, but also taking into account the capabilities and limitations of the whole nano-manipulation system. These strategies will then lead to control schemes making use of the available position and force feedback, as well as of data provided by SEM imaging and virtual reality.

In order to assist untrained operators in the remote handling of nano-objects, the human-machine interface implements haptic interactions, augmented reality and simulation capabilities. Three control modalities are considered:

- Direct control with haptic feedback of virtual/real nano-objects
- Enhanced haptic control featuring assistance functions that reduce the macro-nano gap for the human operator (typically "filtering" the discontinuities of the forces encountered at nano-scale)
- Augmented reality haptic control mixing real and virtual nano-worlds to improve manipulation efficiency.

Finally, the validation of the NANORAC concept is based on (i) the specification, assembling and experimentation of a complete SEM system integrating the hardware and software components previously developed and (ii) providing arrays of evenly distributed CNTs, both vertically standing and horizontally lying, with known uniform properties for test purposes.

At the end of the first year, the consortium has obtained significant results at two different levels:

- Development of the NANORAC basic components (grippers, 3D SEM imaging and simulation modules) in order to independently assess their feasibility
- Definition of NANORAC potential applications and specification of both test scenarios and the architecture of the project integrated test-bed.

The achievements of the second year have clarified the capabilities and limitations of the concept main components:

- Nano-scale simulators
  Two different nano-scale simulators have been developed within NANORAC:
  - The *realistic nano-scale dynamic simulator* that aims at duplicating with accuracy, but in a way that is relevant to nano-manipulation tasks, the physical phenomena encountered at nano-scale
  - The *interactive nano-scale dynamic simulator* that features real time capabilities suited for implementing interactions (especially haptics rendering) with a human user.
- Nano-handling tools
  Specifications and prototypes are now available for the two considered nano-handling tools:
  - The nano-gripper is especially noteworthy for its flexible actuation, anti-stiction CNT coating, nice control curve and force sensing capabilities
  - Designed to apply larger forces, the micro-gripper features easier control through parallel arm grasping, variable capacitor actuators for force measurement and polymer coating to reduce adhesion.

  In both cases, the fabricating processes have been validated and the nano-handling tools tested with respect to several nano-manipulation scenarios.
- 3D SEM imaging
  The current system is able to acquire stereoscopic 2D SEM images and to provide robust nano-object recognition and tracking with good accuracy almost at video rate. Its capabilities have been validated with the above mentioned nano-manipulation scenarios.
- Virtual reality, haptics and nano-manipulation
  Direct haptic feedback has been tested and found unsatisfactory. However, a relevant haptic rendering of nano-scale phenomena was obtained after some trials by intervening on the function that transposes nano-forces in the macro-world and vice-versa. In parallel, nano-manipulation strategies involving "haptic guiding" have been implemented for experiments on real nano-handling tasks.

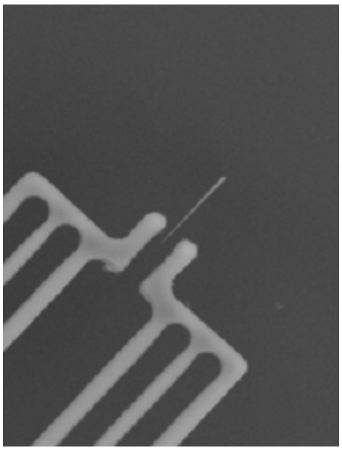
Behind these results, the NANORAC consortium has build a common understanding of nano-manipulation and has implemented very close cooperation between the six partners. Actually, the striking fact about the NANORAC contributors is their complementary expertises that generate fruitful exchanges. We are thus confident of a significant NANORAC impact in the expending domain of nano-technologies and especially in the following four areas:

- SEM imaging
- Nano- and micro-manipulators
- Carbon nanotube technology
- Virtual reality (more precisely, simulation and haptics) at nano-scale.

First of all, developing efficient nano- and micro-manipulation techniques will be a crucial breakthrough in a number of application domains (in RTD departments rather than for production), in particular where Nano or Micro Electro Mechanical Systems (NEMS/MEMS) are considered. But the use of SEM imaging, CNT technology and VR at nano-scale is also more extended and ranges from education in nanophysics to microbiology.

The following key words summarise the expected innovative technological outputs of the project:

- Nano- and micro-manipulation tools with enhanced dexterity and perception capability (design and fabrication process)
- CNT film coating for anti-stiction
- Integration of CNTs on gripper tips for functionalisation
- Dynamic simulation of physical phenomena involved in nano-manipulation
- Control strategies and schemes suited to nano-manipulation
- Hardware for producing stereoscopic images with an SEM
- Software for object recognition, object tracking and 3D imaging of CNTs and grippers from stereoscopic SEM images
- Virtual reality enhancement of nano-manipulation
- Haptic enhancement of nano-manipulation
- Production of CNT arrays with very high uniformity (making use of nano-imprint lithography)
- NANORAC integrated system for advanced micro- and nano-manipulation techniques.



Nano-gripper grasping a carbon nanotube

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