SIXTH FRAMEWORK PROGRAMME
Priority 3 – NMP

NMP-2003-3.4.1.4-1: Characterisation and/or manipulation devices and techniques

NANORAC – STRP 013680

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NANORAC (NANO-Robotics for Assembly Characterisation) is a three-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 (AMiR – D), University of Cambridge (UCAM – UK), Denmark Technical University (DTU – DK), Paris VI University (LRP – F) and Nascatec, a German SME. The EC support amounts to 1 350 000 €. Having achieved most of its objectives, NANORAC ended on 30 April 2008.

1 Project Execution

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 nanomanipulation. 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 with very low depth of field (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 contradiction in performing simultaneously sensing and manipulation.

1.1 Workplan

In the context outlined above, 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 nanomanipulation tasks.

Regarding dynamic simulation, the project aims at providing a realistic Virtual Reality (VR) environment able, in priority order, (i) to enhance the human manipulation skill at nano-scale, (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 (nano-physics). It also exploits 3D perception data provided by an SEM imaging and geometric data extraction module.

The work on manipulation techniques also benefits from nano-physics investigations. Its objectives are twofold:

- Design, production and test of both a nanogripper dedicated to the handling of sub-micron objects (10 nm – 1 µm) and a microgripper for super-micron objects (100 nm – 10 µm)
  It is worth mentioning here the coating of grippers with CNT films as an anti-sticktion feature and the integration of CNTs on the end-effectors to adapt them to the requirements of the tasks.
- Develop manipulation strategies and control
  This work relies on simulations of pick-up and release tasks based on an analytical model of gripping. It aims at implementing manipulation strategies appropriate to nano-physics, but also taking into account the capabilities and limitations of the whole nanohandling 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 features haptic interactions, augmented reality and simulation capabilities. Several control modalities were initially considered, from direct control with force feedback of virtual/real nano-objects to the use of haptics to guide the operator's hand towards a target configuration.

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.

1.2 Micro- and nanogrippers

The core components of the project are the grippers that handle sub- and super-micron objects. Their main requirements may be expressed in terms of capabilities to hold the considered objects, to detach a CNT from its substrate and to release the grasped CNT at a precise position, overcoming the adhesion forces. Translating these general requirements into clear technical specifications implies investigating novel strategies for nanomanipulation as it is exemplified below with the problem of CNT shear off. Two different kinds of grippers were initially taken into account (fig. 1):

- The M-type gripper targeting super-micron objects (and featuring 2-axis force measurement) was developed and reported, but not demonstrated due to the failure of Nascatec, the involved partner, to actively contribute to the project during its final year.
- The N-type gripper (*three-beam nanogripper*), designed and fabricated by DTU, led to extensive experiments with CNTs of 100-1000 nm diameter size. Its dual actuation mode, electrostatic and electro-thermal, provides high flexibility with respect to the constraints of the performed tasks, balancing the external income of temperature or electric charges.

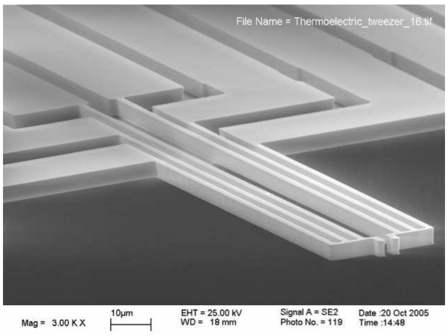

Fig. 1.a: SEM image of a prototype NANORAC three-beam nanogripper (DTU, DK).

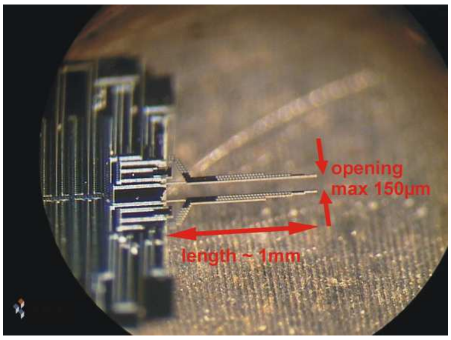

Fig. 1.b: Prototype NANORAC microgripper (Nascatec, D).

Early in the project, tests with the three-beam nanogripper have demonstrated that CNTs were more easily detached by shear pulling rather than by tensile pulling (see fig. 2.a). However, the three-beam nanogripper was often unable to sustain the involved lateral forces and a new N-gripper (*asymmetric ribcage nanogripper*, fig. 2.b) was designed to solve the problem. Optimisation techniques were then employed to increase the efficiency of the N-gripper (*topology-optimised design*). This step forward had another important benefit. The previous experiments were limited to CNTs of 100 nm diameter due to the size of the N-grippers. New fabrication techniques allowed reducing this size, but this also implied reduced strength. Thanks to the topology-optimised approach, it became possible to produce a reasonably efficient "NN-type gripper" by combining (cheap) photo-lithography for large areas and (expensive, but very accurate) electron beam lithography for critical structures. In spring 2008, DTU has thus developed ~ 20 µm nanogrippers with a 330 nm gap, able to handle CNTs in the 10-100 nm diameter range (fig. 3).

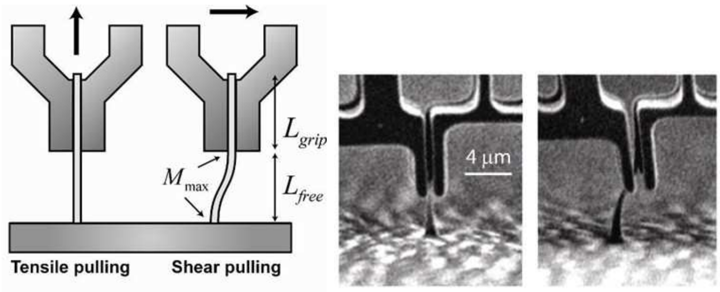

Fig. 2.a: Analysis of CNT detachment from a substrate.

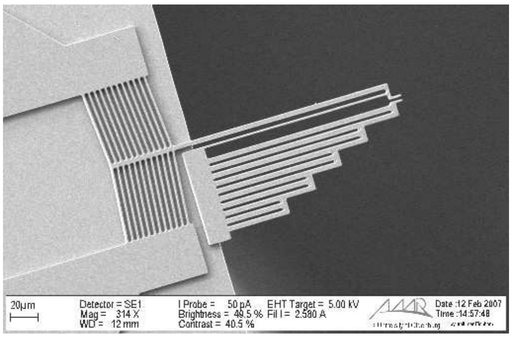

Fig. 2.b: Asymmetric ribcage N-gripper resulting from the previous analysis (DTU, DK).

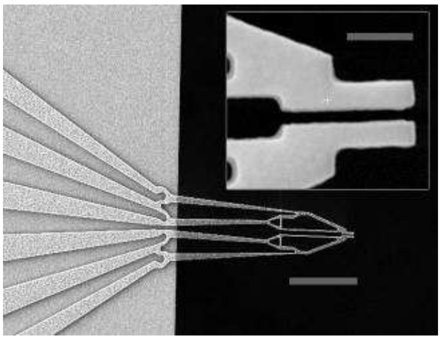

Fig. 3: Topology-optimised NN-gripper (the scale bars are 10 µm and 1 µm; the inset shows a 330 nm gap between the end-effectors). This is probably the smallest tool fabricated up to now by humans (DTU, DK).

The use of CNT films as an anti-sticktion feature to ease the release of nano-objects has been investigated by UCAM and DTU, demonstrating the very good properties of CNT forests. However, the growth of CNTs on very small surfaces like the internal sides of N-grippers proved unexpectedly difficult. Through exchanges with the NANOHAND EU project, it was ultimately concluded that, while CNT coatings is highly suitable for "non-stick workbench" on planar surfaces, minimisation of adhesion is better achieved through nanostructuring with focused ion beam or controlled etching. The problem of CNT growth on small surfaces has also hampered the use of CNTs for tool functionalisation, but this point was indirectly addressed later when the NANORAC system demonstrated its ability to fix a CNT on an AFM tip.

1.3 3D SEM imaging

N-grippers give human operators a capability to handle CNTs in 3-dimension (3D) space rather than to "push" them on a surface (thus in 2D) with a cantilever. However, efficient 3D handling also requires proper 3D perception that is not currently achieved with an SEM which only delivers low quality 2D images. One of the major contributions of AMiR to the project is the development of a

3D SEM imaging system providing (fig. 4):

- Continuous tracking of N-gripper or handled CNT in the SEM working plane (2D tracking)
- Depth maps (3D maps) of the nano-scene generated from pairs of stereoscopic images.

These two functions generate 2D and 3D coordinates that are referenced to the SEM images utilised to compute them. Matching SEM data with virtual reality that uses "absolute" coordinates thus raises a calibration problem that was successfully solved on the NANORAC integrated test-bed. Besides software development, 3D SEM imaging also relies on dedicated hardware components:

- A computer system for the fast acquisition and digitisation of analogue SEM images with real time capabilities consistent with video frequency
- An electro-magnetic lens system able to "deflect the electron beam" and to secure pairs of stereoscopic images without disturbing the experimental setup.

Practical experiments involving CNTs and N-grippers have demonstrated good results with the tracking algorithm running at 5-10 frames per second on full SEM images or 20-25 fps when processing a smaller region of interest. A sub-pixel accuracy of 0.8 pixel has also been achieved (corresponding to 35 nm with a magnification of 2680) and the general robustness was very satisfactory. 3D SEM imaging is the pillar on which virtual reality and haptic enhancements are based and its successful development significantly contributed to the achievements of the NANORAC integrated test-bed.

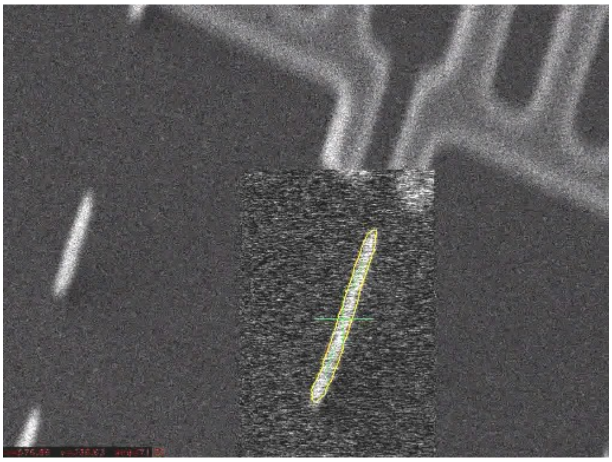

Fig. 4.a: 2D tracking of a CNT using the active contour algorithm (rate: 20 fps, accuracy: 30 nm) (AMiR, D).

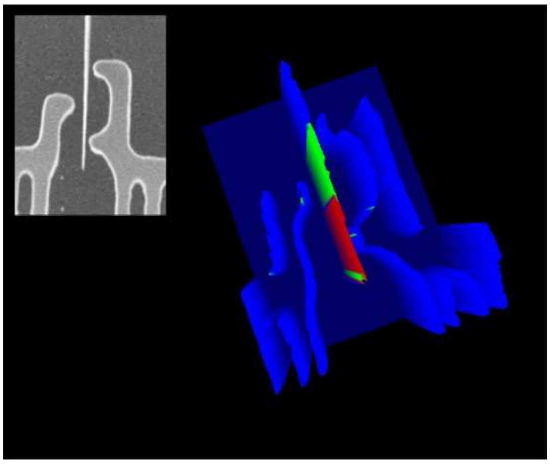

Fig. 4.b: Depth map of a nano-scene computed in about 1s (AMiR, D).

1.4 Nano-simulation and virtual reality

The unfamiliarity of the nano-world mainly results from the nature of the encountered forces: adhesion rather than inertial forces, remote rather than contact forces. To assist human operators in interpreting interactions between nano-objects and to predict their behaviour, they must be provided with some information about the nano-forces applied to CNTs and nanogripper. The problem rests on the difficulty experienced to measure these forces during SEM nanomanipulation and NANORAC thus mainly relies on simulation to generate (visual or haptic) force feedback[1]. For this purpose, LRP (backed by the expertise of DTU) started to build an analytical model of adhesion forces. The task consisted in clarifying the forces encountered at the nano-scale, analysing the abundant literature dealing with nano-physics to extract and develop the relevant knowledge for SEM nanomanipulation. It concluded on the predominance of van der Waals forces (almost no humidity in SEM chambers and necessity to avoid electrostatic interactions that cannot be predicted) applied on cylinder and beam-like geometries. LRP then developed a *realistic nano-scale dynamic simulator* called NanoSim that aims at duplicating with accuracy, but in a way that is relevant to SEM

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[1] The reference to "augmented reality" often found in NANORAC documents actually describes this combination of real and simulated (virtual) data.

nanomanipulation, the physical phenomena encountered at nano-scale (including electrostatic and capillary forces). However, the price paid for accuracy is reduced real time interactivity.

CEA (supported by LRP and AMiR) thus developed a second simulation tool called *interactive nano-scale dynamic simulator* that features real time capabilities suited for implementing interactions with a human user. This virtual reality software (fig. 5) includes rigid models of nanogrippers, CNTs and various nanostructures (AFM tip, TEM grid …), and display dynamic interaction either in a visual way or through haptics. It therefore focuses on comprehensive rendering towards the human operator rather than on accuracy. As described in the next section, this point is mostly important for haptics.

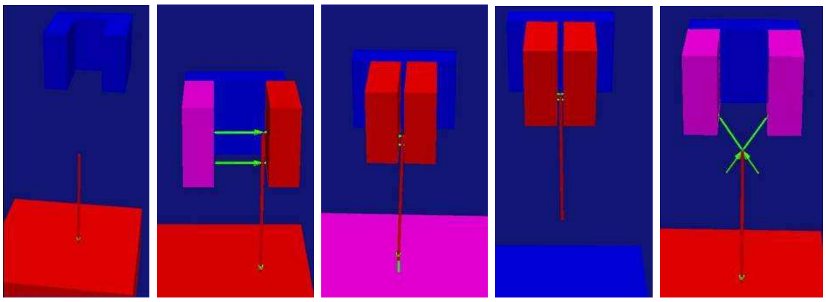
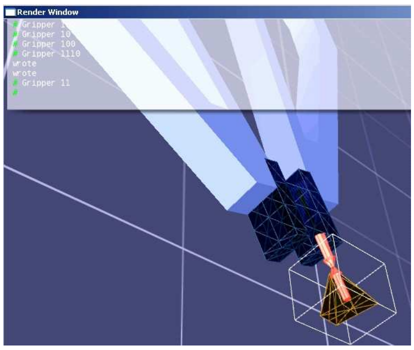


Fig. 5.a: Simulation of a pick and release task (van der Waals forces are displayed as green arrows (CEA, F).



```
# Gripper 1
# Gripper 10
# Gripper 100
# Gripper 1110
wrote
wrote
# Gripper 11
#
```

Fig. 5.b: Topology-optimised N-gripper approaching an AFM tip (CEA, F).

1.5 Haptics and nanomanipulation

Basically, three haptic coupling schemes were implemented and tested in the frame of the project:

- *Direct haptic teleoperation*
  Haptic feedback is directly generated from nano-force measurements or on accurate (as much as possible) dynamic simulation. This is the classical scheme used in the macro-world for master-slave force feedback remote handling systems.
- *Enhanced haptic teleoperation*
  It implies "modifying" the nano-physical laws in order to provide the human operator with more efficient perception of the nano-forces in the different phases of a nanohandling scenario. The enhanced scheme is necessarily based on the simulation of some kind of "pseudo nanophysics".
- *Augmented reality haptic teleoperation*
  In this last scheme, the purpose of haptic feedback is to guide the human operator's hand in order to successfully perform nanomanipulation tasks. It rests on software-generated commands (virtual guides) that "attract" the nanogripper towards its target or restrain its degrees of freedom to avoid undesired configurations.

To experiment with these various haptics and manipulation schemes, LRP has developed a micromanipulation test-bed (fig. 6) featuring 2D force measurements that are mandatory to compare the outputs of simulation with real nano-world data. Using a Virtuose 3D 15-25 haptic arm from Haption, a CEA spin off, it was then possible to validate haptic coupling schemes in several test configuration: haptic arm and VR simulation software operating alone, haptic arm and VR software coupled with the LRP test-bed and later haptic arm and VR simulation software coupled with the Nanorac integrated test-bed.

Regarding haptic feedback, the results may be summed up as follows:

- When rehearsing in virtual reality a prospective nanohandling scenario, the simulation of the encountered nano-forces based on accurate nanophysics provides the best benefit since it allows the scenario designer to assess its feasibility and to select the most relevant configurations.

- To assist human operators performing real nanohandling tasks, *direct haptic teleoperation* is both impractical (almost impossible to implement in a real time context due to the dynamic of nano-forces) and inefficient (the rendered force variations are often imperceptible or confusing).
- For free space movements, *virtual guides* are generally the proper option.
- When the handled objects are close to the surrounding nanostructures, it appears that *simulating contact forces using the macro-world physical laws* is a good approach as it provides the human operator with contact information expressed in a familiar way.
- However, in some cases when the peculiarities of the nano-forces have a strong impact on the way to perform a nanohandling task, *enhanced haptic teleoperation* may offer very efficient metaphors (for example, applying a constant effort on a nano-sphere and roll it despite the instability conditions of repulsive regime). On the other hand, these metaphors must be designed and activated/deactivated according to specific situations.

Simulated forces may thus definitely generate useful information for a successful manipulation at micro/nano-scale when the force measurements are not available or not exploitable.

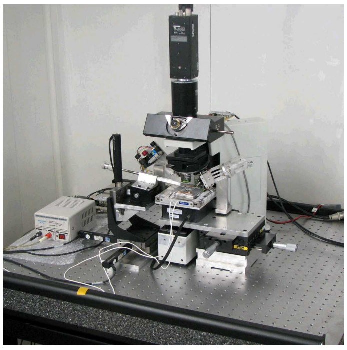


Fig. 6.a: LRP test-bed.

Fig. 6.b: Virtuose 3D 15-25 haptic arm developed by Haption, a CEA spin off; it provides 6 axis control and implements force feedback on 3 of them.

1.6 CNT samples

In order to perform repeatable experiments with the NANORAC integrated test-bed, it is necessary to work with samples of CNTs featuring uniform characteristics. Two kinds of CNT samples were considered:

- Wafer scaled vertically aligned CNTs
- Horizontally aligned single-walled carbon nanotubes (SWCNTs).

To fabricate vertically aligned CNTs, UCAM developed a technique based on nanoimprinting rather than classical electron beam lithography for the following reasons:

- Simple technique when compare to electron beam lithography
- High throughput capabilities
- Low cost for next generation technology
- High initial cost of the master-but other moulds can be reproduced from this master.

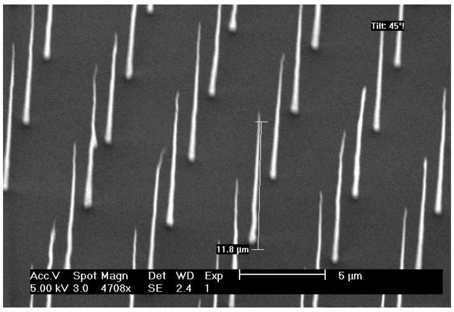


Fig. 7.a: Array of vertically-aligned CNTs (UCAM, UK).

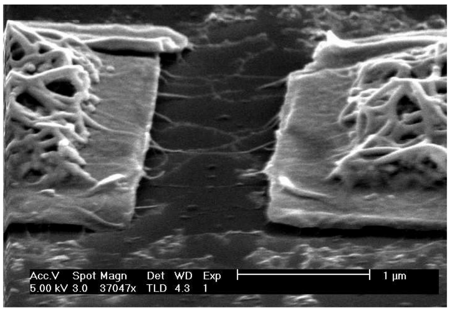


Fig. 7.b: Horizontally-aligned CNTs (UCAM, UK).

1.7 Nanorac integrated test-bed

During the last year of the project, the main goal for all the active partners was the assembly of the NANORAC integrated test-bed gathering all the components previously developed (fig. 9): (i) a nano-handling station (fig. 8) specifically developed by AMiR, (ii) the N- and NN-type grippers designed and fabricated by DTU, (iii) the AMiR SEM imaging system and (iv) the haptic, virtual reality and manipulation supervisor subsystem provided by CEA and LRP. The nanotubes produced by UCAM were also widely used to test the system on several nanomanipulation scenarios. Besides delivering the components they have developed, the project partners co-operated very closely to achieve the integration work, in particular AMiR/LRP who worked out the data communication architecture and the interface between virtual reality and the nanohandling station, and DTU/AMiR who did intensive manipulation experiments during the whole project duration.

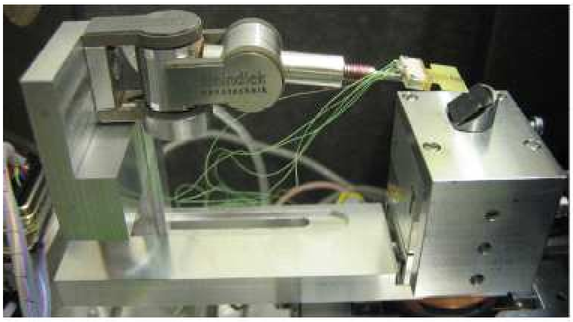


Fig. 8: The nanohandling station. It rests on a base plate supporting a 3-axis micromanipulator and a high-resolution nano-positioning stage. The micromanipulator holds the N-gripper while the home and target substrates (where to catch and release CNTs) are located on the nanostage; most of the time, it is thus the CNTs that move w.r.t. the fixed gripper. The whole setup is installed inside the SEM vacuum vessel (AMiR, D).

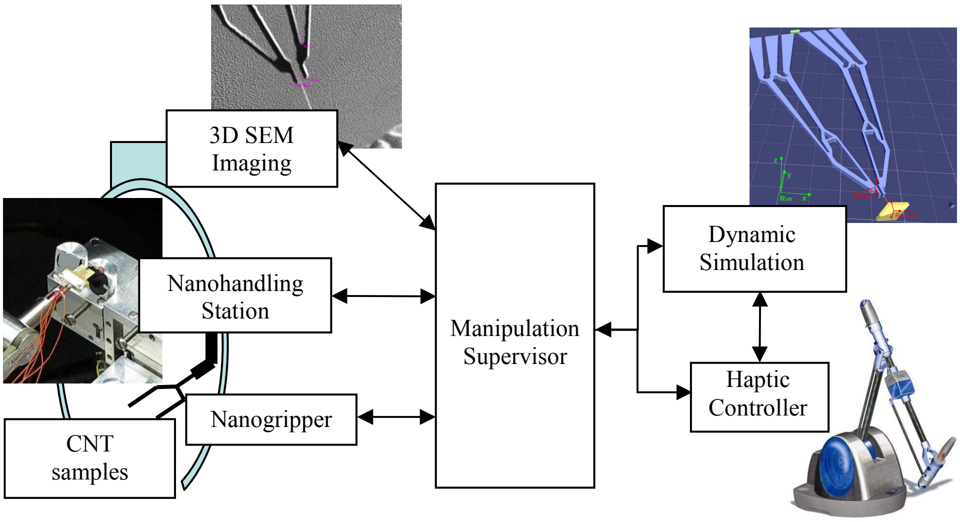


Fig. 9: General architecture of the NANORAC test-bed.

During the first year, the project partners defined 4 representative scenarios (fig. 10) and the whole system was thereafter specified to perform them:

- Scenario A: pick up and place a CNT on a TEM grid
- Scenario B: pick up and place a CNT onto a pair of microelectrodes
- Scenario C: pick up and place 2 CNTs into a cross junction
- Scenario D: pick up and bond a CNT onto an AFM tip.

When completed, the integrated system was extensively operated on scenarios A, B & D in order to:

- Validate the robotic components (mainly the nano-positioning system and the N- and NN-type nanogrippers) that allow a human operator to control the grasping of a carbon nanotube on a source substrate, its detachment from this substrate, its displacement towards a target substrate and its accurate release on a target nanostructure
- Demonstrate how the human perception of nanohandling tasks may be enhanced through 3D imaging, virtual reality, haptic feedback and manipulation supervision.

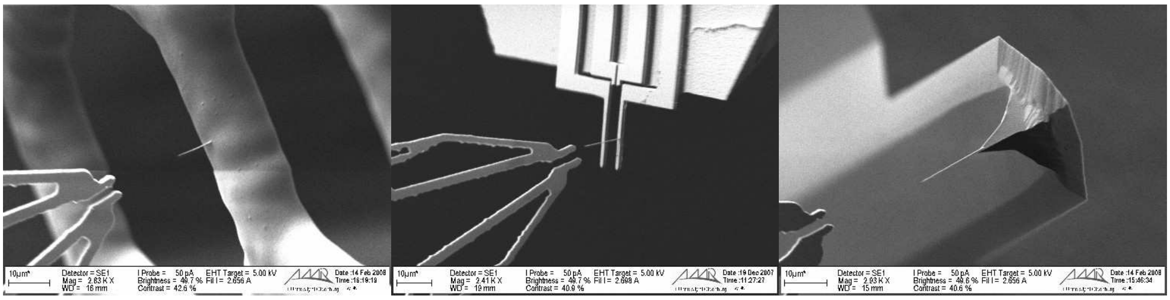


Fig. 10: SEM images showing the completion of scenarios A, B and D using the NANORAC system and N-grippers (DTU, DK).

3D SEM imaging, virtual reality and haptic enhancement were in particular successfully validated on scenario D that was divided in a number of elementary tasks:

1. Approach CNT with the micromanipulator
2. Calibrate the virtual nano-scene by observing known nanostage motions through SEM imaging
3. Catch CNT using the nanostage with 3D visualisation and haptic feedback of contact forces
4. Detach CNT with the nanogripper that successfully sustain shear off reaction forces
5. Approach AFM tip with the micromanipulator
6. Calibrate the new virtual nano-scene as in 2. (all calibration procedures are automated)
7. Position the CNT onto the target structure using the nanostage with 3D visualisation and haptic guidance (fig. 11.a)
8. Fix the CNT on the AFM tip using electron beam
9. Test and characterize the assembled device: AFM scan with the CNT-AFM-probe (fig. 11.b; this actually results in a kind of tool functionalisation as mentioned in section 1.2).

Two videos demonstrating this scenario have been prepared and uploaded on the nanotechnology section of the YouTube website.

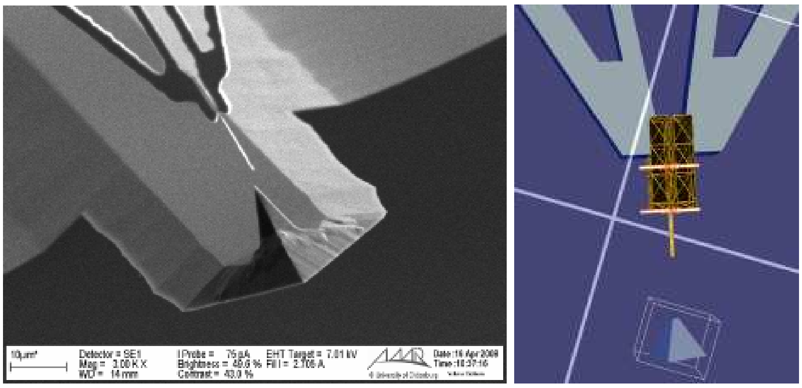


Fig. 11.a: SEM and virtual images captured during completion of scenario D.

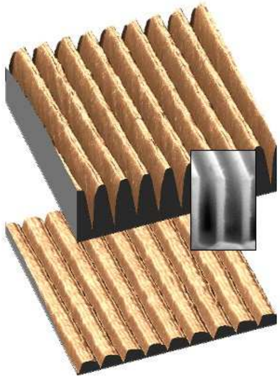


Fig. 11.b: Improvement in AFM scanning with CNT-equipped AFM tip.

The conclusion of the performed experiments may be summed up as follows:

- The detachment of a 100-1000 nm diameter CNT from a source substrate and its accurate positioning on a target structure has been definitely demonstrated
- The capability of performing the same tasks on 10-100 nm CNT is clearly within reach

- The processing of SEM images to achieve 2D tracking and 3D perception has been validated on representative practical nanohandling scenarios
- The benefit of virtual reality that provides the human operator with easy to handle 3D views of a calibrated virtual nano-scene duplicating the real environment has been established
- Several schemes for using haptic feedback have been investigated and their respective benefits assessed with respect to the considered nanohandling tasks.

1.8 Management

Behind these results, the NANORAC consortium has build a common understanding of nano-manipulation and has implemented very close cooperation between the project partners. Actually, the striking fact about the NANORAC contributors is their complementary profiles and expertises that generate fruitful exchanges:

- Four academic organisations evaluated according to the quality of the scientific papers they produce:
  - AMiR: nano-robotics
  - UCAM: CNT technology
  - DTU: nano-fabrication processes
  - LRP: micro- and nanomanipulation
- One applied research organisation that mainly aims at securing intellectual property rights:
  - CEA specialised in virtual reality
- One industrial company whose raison d'être is to develop viable commercial products and/or services on nanotechnology:
  - Nascatec.

During the project three years, the established collaboration may be qualified as exemplary. Apart from the Kick-off Meeting, the Mid-term and the Final Reviews, 4 plenary meetings were held, as well as 4 "working weeks" about nanomanipulation, integration and experiments. It is therefore most unfortunate that Nascatec stopped its activities without explanation in the middle of the third year.

2 Dissemination and use

In the course of the project, several application domains have been identified as potential targets for the NANORAC developments in nanomanipulation:

- Life science, especially the pharmaceutical industry (fast and low cost in-vivo and ex-vivo testing …) and genetic engineering
- Chemistry (for fast and reliable analysis)
- Information technologies for opto- and microelectronic production (quality control, handling of nano-components and direct combination of opto- and semiconductor components …)
- Automotive industry through advanced nano-systems like gas sensors for the qualitative control of the air inside a vehicle.

These domains share very high expectations in MEMS/NEMS (Micro/Nano Electro Mechanical Systems) for which nanomanipulation will be required to efficiently perform research, prototyping, evaluation and quality control. On the opposite, the usefulness of robotised nanohandling for large scale fabrication is less certain. Nevertheless, some of the technologies considered within NANORAC have a larger application domain. This is obvious for SEM imaging, non-sticking CNT films or simulation and haptics that are relevant independently of nanomanipulation.

Since the beginning of NANORAC, the expected innovative technological outputs of the project were summarised by the following key words:

- Nano- and micromanipulation tools with enhanced dexterity and perception capability (design and fabrication process)
- CNT film coating for anti-sticktion
- Integration of CNTs on gripper tips for functionalisation
- Dynamic simulation of physical phenomena involved in nanomanipulation
- Control strategies and schemes suited to nanomanipulation
- 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 nanomanipulation
- Haptic enhancement of nanomanipulation
- Production of CNT arrays with very high uniformity (making use of nano-imprint lithography)
- NANORAC integrated system for advanced micro- and nanomanipulation techniques.

It is now relevant to consider all these technological developments with respect to the achieved results and exploitation plans. This has been done here in tabular form for sake of clarity (table 1).

Besides transferring knowledge to the industry or to next users, the NANORAC team has planned an extensive programme of dissemination activities that has been already significantly implemented:

- Results of the 1st year (during the project 2nd year):
    - Object tracking by SEM images (AMiR)
    - Capillary force analysis for nano-robots (LRP)
    - Non-stick CNT film (DTU, UCAM)
- Results of the 2nd year
    - VR for nanomanipulation (LRP, CEA)
    - Haptic manipulation (CEA, …)
    - Integration of CNTs on cantilevers (DTU, UCAM)
    - Nanogripper manipulation experiments (DTU, LRP & AMiR)
    - Force measurement in nanomanipulation (CEA, all)
- Results of the 3rd year
    - M & N Type grippers experiments (DTU, Nascatec)
    - Nano-imprint (UCAM, DTU)
    - Application paper (DTU, all)
    - Results of NANORAC (CEA, all).

A small selection of the most important papers published on Nanorac developments is given below:

K. Gjerde, M. F. Mora, J. Kjelstrup-Hansen, T. Schurmann, L. Gammelgaard, M. Aono, K. B. K. Teo, W. I. Milne, P. Bøggild. *Integrating nanotubes into microsystems with electron beam lithography and in situ catalytically activated growth*. Physica status solidi (a), 203, 6, 1094-1099 (2006).

T. Sievers, M. Jähnisch, Ch. Schrader, S. Fatikow. *Vision feedback in an automatic nanohandling station inside an SEM*. 6th Int. Optomechatronics Conference on Visual/Optical Based Assembly and Packaging, SPIE's Optics East, Boston, MA, USA, 1-4 October, Vol. 6376, 63760B (Best Paper Award) (2006).

M. Jähnisch, S. Fatikow. *3D vision feedback for nanohandling monitoring in a Scanning Electron Microscope*. International Journal of Optomechatronics, vol. 1, no. 1, pp. 4–26 (2007).

K. Carlson, K. N. Andersen, V. Eichhorn, D. H. Petersen, K. Mølhave, I. Y. Y. Bu, K. B. K. Teo, W. I. Milne, S. Fatikow, P. Bøggild. *A carbon nanofibre scanning probe assembled using an electrothermal microgripper*. Nanotechnology, 18, pp. 345501 (2007).

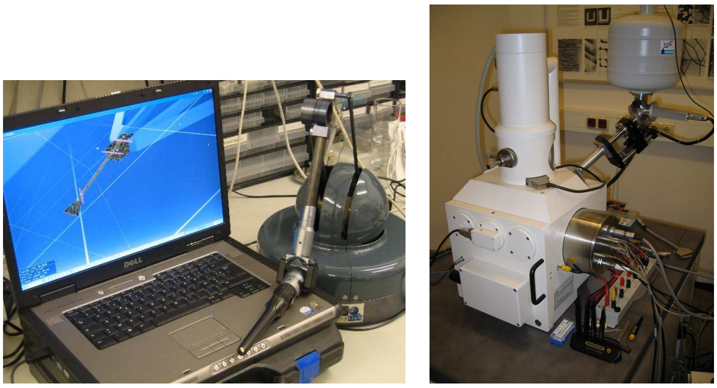
V. Eichhorn, K. Carlson, K. N. Andersen, P. Bøggild, S. Fatikow. *Nanorobotic manipulation setup for pick-and-place handling and non-destructive characterization of carbon nanotubes*. IROS 2007, IEEE/RSJ International Conference on Intelligent Robots and Systems, Oct. 29 – Nov. 2, San Diego, USA (2007).

H. Xie, J. Vitard, S. Haliyo, S. Régnier, M. Boukallel. *Calibration of lateral force measurements in atomic force microscopy*. Review of Scientific Instrument, p. 033708 (6pp) (2008).

S. Haliyo, on behalf of the NANORAC Consortium. *SEM manipulation with real time virtual reality and haptic feedback*. Invited talk in Workshop on Grand Challenges in Microrobotics and Microassembly, RSS'08 Robotics: Science and Systems, Zurich, June 28 (2008).

H. Xie, J. Vitard, S. Haliyo, S. Régnier. *Calibration and nonlinearity compensation for force application in AFM nanomanipulation*. IROS 2008, IEEE/RSJ International Conference on Intelligent Robots and Systems, Sep. 22 – 26, Nice, France (2008).

K. N. Andersen, D. H. Petersen, K. Carlson, K. Mølhave, O. Sardan, A. Horsewell, V. Eichhorn, S. Fatikow, P. Bøggild. *Multimodal electrothermal silicon nanogrippers*. In press in IEEE Transactions on Nanotechnology (2008).



More information on NANORAC may be found at:
http://www.amir.uni-oldenburg.de/en/12603.html,
http://www.nanosystemsengineering.dk/index_files/nanogripper.htm and
http://www.amir.uni-oldenburg.de/videos/NANORAC_movie.wmv,

or by contacting the project coordinator:
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Table 1: Nanorac results, achieved performances and exploitation plans.

Developed modules	***Main features or performances***	***Exploitation plans***
Nano- and micromanipulation tools with enhanced dexterity and perception capability (design and fabrication process)		
• Specification, development and validation of several types of N- and NN-nanogrippers • Fabrication methods	• Handle objects of 10 nm size • Detach a CNT from its substrate • Release it in a precise position • Mix and match nanofabrication process.	The nanogrippers will be marketed by a DTU spin off in 2009. DTU is also in contact with a German company.
Specification and development of a micro-gripper	• Apply higher forces • Feature limited force measurement capability • This M-gripper was not demonstrated.	Nascatec will probably add this micro-gripper to its product range (to be confirmed).
CNT integration for anti-sticktion & functionalisation		
CNT film coating for anti-sticktion	• Demonstration of the powerful anti-sticktion properties of CNT films • CNT growth on small nanogripper sides unexpectedly difficult. Solutions exist to deal with adhesion forces when releasing a nano-object (milling uneven surfaces with focused ion beam lithography). This development is thus relevant for large surfaces, rather than for nanogrippers.	DTU and UCAM are managing the exploitation of this project output.
Integration of CNTs on gripper tips for functionalisation	• Difficult due to the problem of CNT growth on small surfaces • Possible using NANORAC nanohandling system (CNT placed on AFM tip).	It is expected to extend and automatise the process in the frame of the EU NANOHAND and German ZUNAMI projects.
Dynamic simulation of physical phenomena		
Realistic nano-scale dynamic simulator	The simulation software mentioned here are specifically developed to overcome the difficulties of nano-interactions: • Very high stiffness encountered in the nano-world • Small interaction distances. The first one focuses on simulation accuracy, while the second rather aims at real-time performances consistent with haptic coupling.	Exploitation as an open source software for education purpose available in 2009 (LRP).
Interactive nano-scale dynamic simulator supporting haptic interactions		CEA is considering releasing this simulator as a module integrated in the XDE software marketed by Haption (a CEA spin off).
3D SEM imaging		
Hardware and software for stereoscopic depth detection using SEM images	This component has been fully validated in the frame of the project, demonstrating its capability to generate depth maps of SEM-observed nano-environments.	Exploitation has been initiated by AMiR who is in close contact with three interested companies.
Software for object recognition and tracking	Complete validation of the software was achieved during the project: • Robustness of the tracking algorithms • Accuracy of the delivered positions and orientations.	

Virtual reality and haptic enhancements of nanomanipulation The control strategies investigated by LRP are enclosed in this component, in particular as virtual guides.	• Successful results with 3D visualisation providing information about contacts and nano-force interactions • Evaluation of several haptic coupling schemes: o Indifferent results with direct haptic coupling scheme o Development of some efficient enhanced coupling schemes o Validation of virtual guides o Interest in "macro-like" haptic feedback.	Exploitation is considered by CEA and LRP in the fields of education and nanohandling for task preparation and execution, as well as for tool design.
Production of CNT arrays with very high uniformity (making use of nano-imprint lithography)	• Wafer scale arrays of vertical carbon nanotubes • Wafer scale arrays of horizontal carbon nanotubes	Exploitation is managed by UCAM that plans a technology transfer towards a company developing solutions for nano-imprint lithography.
Nanomanipulation test-beds		
NANORAC integrated nanohandling test-bed	This advanced research nanomanipulation tool features: • Nano-grasping and nano-robotics capabilities • 3D SEM imaging • Nano-scale simulator • VR and haptic nanohandling enhancement • It can be used by untrained operators.	AMiR and LRP intend to pursue the development of micro- and nanohandling systems as an input for the medium and long-term strategy roadmap of European research. The gathered knowledge and the developed components will therefore constitute excellent inputs for new European or National research projects.
LRP micromanipulation test-bed	While it is unsuitable for 3D manipulation, this second test-bed integrates: • Cantilever-based tools • Position and force measurement capabilities • Interactive simulation • VR and haptic enhancement. These features make it a remarkable research tool for studying micromanipulation.	