MiCRoN	*<IST–2001-33567>* ***Miniaturised co-operative Robots advancing towards the Nano Range***

Public Report

Covering period 1-March-2004-31-August-2005

Report Version: 1.0

Report Preparation Date: 20-February-2006

Classification:

Contract Start Date: 1-March-2002 Duration: 31-August-2005

Project Co-ordinator: Ramon Estaña, UNIKARL

Partners:

UNIKARL: University of Karlsruhe, Germany

DMS: The Angström Laboratory at Uppsala University, Uppsala, Sweden,

EPFL: Institute de Systèmes Robotiques, Lausanne, Swizerland

FhG: Fraunhofer-Institut für Biomedizinische Technik, St. Ingbert, Germany

NTUA: National Technical University of Athens, Athens, Greece

SHU: Sheffield Hallam University, Sheffield, England

SSSA: Scuola Superiore di Studi Universitari e Perfezionamento Sant' Anna, Pisa, Italy

UB: Departament d'Electrònica, Universitat de Barcelona, Barcelona, Spain

Project funded by the European Community under the "Information Society Technologies" Programme (1998-2002)

MiCRoN Final Review Report

1 Executive Summary

1.1 Introduction

The MiCRoN project, No. IST 2001-33567, aimed at the development of a new Microrobot system based on flexible mobile, 1cm^3 sized robots acting autonomously. The eight project partners started in March 2002 with the development of a system based on the results from the Miniman Project.

The MiCRoN project's outcome is a major contribution in the field of micro-mechatronic components. A cm^3 robot design has been devised using low voltage piezo actuators and hybrid on-board electronics. Several micro tools have been developed:

- Millimetre-sized grippers for the 3D assembly of meso-scale objects,
- A robot-mounted micro syringe chip for the injection of substances into living cells
- AFM tools for standard AFM imaging and using functionalised nano tips for biological experiments

The robot actuators have been developed using a novel rapid prototyping process for multilayer piezoceramics; the robot hardware consists of a cubic centimetre onboard electronics module. Another major contribution of the project are methods for wireless micro robot operation. A power floor has been built as a working prototype, which transmits electrical energy to mobile units operating on a 250×250 mm^2 area. Infrared communication schemes have been developed for controlling a small group of robots. An advanced control system has been realized including an implementation of the progressive Kalman Filtering Theorem. This software package includes all software needed for robot control, navigation, planning, simulation and user interfacing. For the integrated on-board vision system, a camera, which can be mounted on mobile micro robots, has been developed into a working prototype. This system can generate 3D data of micro manipulation scenarios. The computer vision system developed offers a broad range of stable recognition algorithms for micro handling applications. In the field of object localization, the global localisation system represents a major achievement. This system has reached final prototype state with a position resolution of about 4 µm over the complete size of the workspace. By using phase shifting algorithms the resolution of the system is about 1µm.

1.2 The Consortium

The consortium for this project consists of eight partners:

Partic. Role*	Partic. No.	Participant Name	Participant short name	Country	Role
C	1	Institute for Process Control and Robotics, Universität Karlsruhe (TH)	UNIKARL	Germany	Coordinator; Responsible for the localisation system, coordination and integration
P	2	The Ångström Laboratory at Uppsala University	DMS	Sweden	Micro Actuators and robot hardware integration
P	3	Institut de Systèmes Robotiques at Swiss Federal Institute of Technology, Lausanne	EPFL	Switzerland	Micro Actuators and robot hardware integration

P	4	Fraunhofer-Institut für Biomedizinische Technik, St. Ingbert	FhG	Germany	Biological experiment preparation, Novel tools like Syringe Chip
P	5	National Technical University of Athens	NTUA	Greece	Simulation and software development
P	6	Microsystems and Machine Vision Laboratory (MMVL) at Sheffield Hallam University	SHU	United Kingdom	Vision software, on-board sensors
P	7	Scuola Superiore di Studi Universitari e Perfezionamento Sant'Anna, MiTech Lab, Pisa	SSSA	Italy	Micro grippers, Assembly demonstrator
P	8	Departament d'Electrònica, Universitat de Barcelona	UB	Spain	Electronic hardware development

Table 1: The consortium of the MiCRoN project

The system components' key figures can be summarized as follows:

- **Mobile micro robots:** cm^3 sized micro robot platform with 3 DOF (x, y, θ_z)
  - **Wireless powering:** A 220 mm × 200 mm working area capable of transmitting 330 mW wirelessly
  - **Micro Grippers:** fabricated by EDM, for pick & place operations of 30 µm spheres, 35 µm wires or 150 µm resistors
  - **Micro machined syringe chip for cell penetration:** $2.2 \times 2.2 \times 1$ mm^3.
  - **AFM tools:** with sensors and actuators featuring very compact dimensions and low-power operation
  - **Piezoceramic miniature motors:** For driving a robot gripper and supplying the robot with an additional DOF
  - **Monolithic piezoactuators**: suitable for any application with large workspace and high accuracy requirements. Velocities up to 0.5 mm/s, thrust force up to a few N
  - **Piezoactuators for micro-robotics** and the respective processes for rapid prototyping
  - **Mixed-signal ICs:** to control several piezoactuator channels of a mobile micro robot and a AFM module
  - **On-board electronics module**
  - **Miniaturized wireless communication module:** for micro robotic applications
- **Handling experiments**: multi-robot scenarios for cell-handling experiments, cell-injection experiments and involving the 3D assembly of meso-scale products and objects using a micro soldering process
- **Vision and Position Sensors**: These are sensor systems which provide the following information to the system:
  - A sensor system for **global localisation** system gaining information about the position of the robots – needed for control and navigation - in the 240 mm × 240 mm sized working area
  - A vision sensor to provide **local images**: A Miniman IV robot has been equipped with a special miniature CMOS- camera.

  - A robust and flexible vision system for the **recognition** of the robots
  - **3D-Object recognition and Scene interpretation** based on local images
- **System control**: this is the “brain” of the complete system and involves the following points
  - Motion control of the robots assuring the mobility and ability to manipulate
  - Integration of both the robot localisation system and the object recognition
  - Automatic path planning and collision avoidance
  - Collective and co-operative behaviour of the microrobots
  - Supervision for on-line controls and failure handling

2 Project Objectives

2.1 State of the Art

During the project duration, two major Microrobotic projects run in the United States and in the European Country:

1. NANOWALKER, developed at the MIT, Massachusetts, already finnished
2. Nanorac, an EU-project currently running

Let us take a closer look to these two very interesting research projects.

2.1.1 The MIT NanoWalker Microrobot

The goal of this project is the development of a very small, untethered and fully autonomous instrumented robot capable of subatomic movement and was the first project (likewise the PROHAM[1] from IPR) that gives a new paradigm in the way instruments are built while providing a platform for a new range of applications. It involves

1. the investigation of a new legged locomotion based on piezo-actuators with advanced micro-assembly techniques applied to complex embedded electronic systems;
2. the development of new miniature instruments, micro-manipulators, integrated behaviour for controlling, searching and scanning at the atomic scale and
3. the development of a subatomic navigation system.

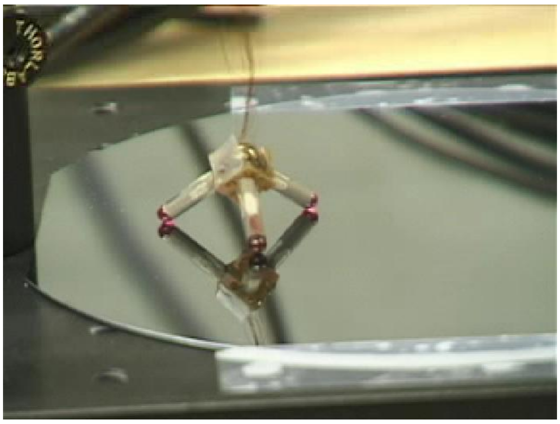


Figure 1: State of the Art: The NanoWalker Microrobot from the MIT, USA

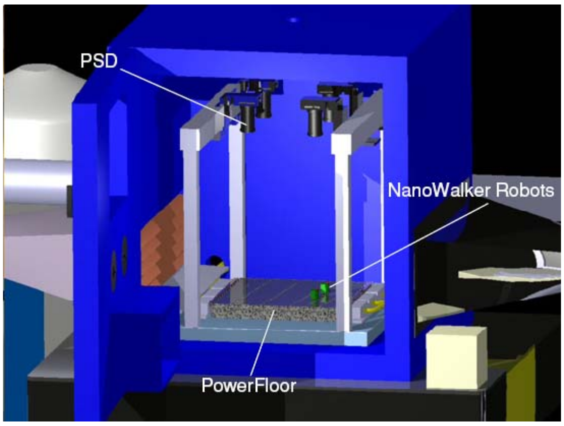


Figure 2: State of the Art: The NanoWalker Microrobot setup with navigation and powerfloor[2]

This Microrobot system has gained to a high complex system now. Several robots are working together as a cooperating system on a Powerfloor equipped with electrodes, over which the robots are supplied with energy. An IR-communication enables – together with a high precise navigation system – a closed loop control for handling and driving tasks.

---

[1] Munassypov R., Grossman B., Magnussen B. and Fatikow S.: **Development and Control of Piezoelectric Actuators for a Mobile Micromanipulation System**. In: Proc. Of the Int. Conference on New Actuators (Actuator '96), pp 213-216, Bremen, Germany 1996

[2] Martell, S: **Special surface for power delivery to wireless micro-electro-mechanical systems;** NanoRobotics Laboratory, Department of Computer Engineering and Institute of Biomedical Engineering, Ecole Polytechnique de Montreal (EPM), Campus of the University of Montreal, PO Box 6079, Station Centreville, Montreal (Quebec), H3C 3A7, Canada; Published 6 September 2005

Each robot is equipped with an AFM-tip for local navigation (similar to the AFM assembled to the -robots). All in all, the NanoWalker project is a real competitive and well done realisation of a functional Microrobot system. Furthermore, this project has the big advantage of a long-time research intention.

2.1.2 The Nanorac Project (EU 6th Framework)

The objectives of the Nanorac project are to develop efficient instrumentation for measurement, analysis and manufacture at the nano-scale. In fact, this is a robotic system, which will allow an untrained operator to interact with nano-scale objects for characterization, sorting and assembly tasks.

This approach makes it necessary to study and resolve different problems in order to create a robust robotic system capable of the desired functionalities. The scientific approach developed in this project is applicable to all nano-scale objects but as a concrete example, will concentrate on the carbon nanotubes.

There are two major issues that shall be reached:

1. A precise manipulation calls for a clear understanding of the physical specificities of the nanoscale. Secondly, based on this knowledge, adapted manipulation tools and grippers can be designed. Then, given precise pick-up and release tasks, manipulation strategies and corresponding control schemes must be established.
2. An important point is to provide the human operator with an optimal mean to control the operation. The difficulty is that the classical optical methods don't work because of the smaller than light wavelength size of the targeted objects. Techniques such as SEM (Scanning Electron Microscopy) exist but the resulting 2D images do not provide sufficient position information for a precise manipulation. A 3D virtual reality reconstruction of the manipulation is a good solution to provide the user with a complete set of information on the operation. Moreover, a haptic interface will furnish a most intuitive interaction between the operator and the system.

2.1.3 Comparisons with the MiCRoN Project

Compared with the MiCRoN-Projects, Nano structures will be handled and used. In the MiCRoN-project, the handling of a much wider range of parts like cells and other micro-scaled mechanical parts is the main objective.

Another big difference is the ability of using tools with complete different functionality. This makes the robots very flexible.

Last. But not least, uses a high level of integration (electronics and mechanics) and represents a cutting edge technology implementation. Additionally, navigation and communication together with task-planning possibilities makes this system high efficient and again most flexible.

The goal of this project is to develop a system that is based on a cluster of small (1 cm^3) mobile autonomous micro robots. These microrobots are working untethered, and each robot is equipped with onboard electronics for control and communication. It can co-operate to accomplish a range of tasks associated with assembly and processing from the nano- to the micro-range. To realise this system, a number of objectives had to be achieved. In Figure 3 an overview of the project goal is depicted.

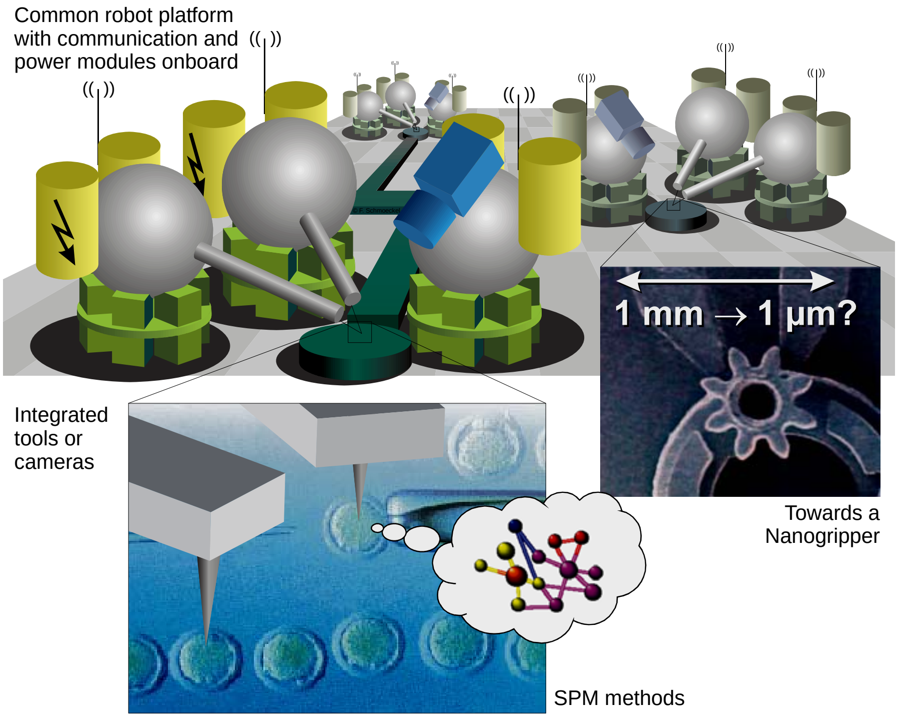


Figure 3: The visionary project objectives for the MiCRoN project

2.1.4 The Microrobot Platform

The platform consists of a locomotion system allowing a velocity of about 0.5 Millimetre per second combined with a large working area (220 by 200 mm^2) and nanometer resolution. The robots navigate on a flat, horizontal surface using holonomic movements. The main tasks of the locomotion system are to bring the handling-tools (*e.g.* grippers) to the region of interest or to transport micro objects.

The hardware platform incorporates advanced, beyond state-of-the-art technological solutions. The system design enhances the performance achievable by each individual microrobot by suitably distributing various mechanical degrees of freedom (DOF) among the microrobots to enable complex object handling and manipulation.

A mechatronic system design approach is also being pursued in the design of the microrobot platform. The mechanisms, sensors, actuators, drives, embedded control, interfaces and energy supply, are designed in an integrated manner, thus optimising size and functions. The platform comprises several types of tools for grasping mesoscopic objects, tools for nano-manipulation and tools for inspection or measurement tasks.

Other degrees of freedom (vertical rotation) are added to the locomotion system that holds the manipulating tools, according to the specific robot task. The drives for the tools are extremely compact (few mm^3) and have a few millimetres working range with nanometric resolution. Detailed specifications in terms of degrees of freedom and working range have been defined according to the requirements of handling experiments which have been determined at the beginning of the project.

Piezo actuators have been incorporated due to their excellent resolution. An onboard IR module assures the communication with a host computer. The onboard electronics controls the robot motion, generates and amplifies the driving signals for all actuators and tools and pre-processes the signals from the on-board sensors.

Power management was a critical issue to ensure autonomous operation of the robot for the longest possible time. A power consumption of significantly less than 1 W per robot was aspired. In particular, heat management was important from both an energy saving point of view and to avoid detrimental effects resulting from overheated system components or manipulated objects.

The co-operative control strategy required an efficient communication system that was developed to meet the special requirements of MiCRoN. Finally, a localisation system working touchless and with high precision, provides the coordinates of the robots to the control system, so that a closed loop control of the robot movements is realised.

2.2 Handling Experiments

In order to assess the performance and evaluate the capabilities of the proposed system for the intended micro- and nano-manipulation tasks, two different scenarios have been devised.

The first scenario involves the *3D assembly* of meso-scale products. A specific class of devices, representative of a future range of new products that can be manufactured using the MiCRoN system, has been selected for this handling experiment. At the beginning of the project, it has been planned to assemble components for biomedical micro-endoscopes using the robots. But, during the project progress, a simplified task was chosen because of the complexity of the proposed goal: Two robots soldering a small electronic part onto a PCB.

The second scenario is derived from the field of *biological and biomedical nano-manipulation*. A manipulation experiment taking place in a "desktop" cell laboratory operated by mobile microrobots has been defined that requires the co-operation of the MiCRoN robots for 3D positioning and orienting of single cells as well as for cell cultivation. In this multi-station single cell diagnostic environment, the microrobots are used for the manipulation of biological particles and for the testing and characterisation of cells.

2.3 Beyond Grasping: Novel Tools

The assembly of the meso-scale components involves novel, millimetre-sized grippers designed for the 3D assembly of a range of components, both rigid and flexible. For the biological handling experiment, novel tools for grasping and manipulating micrometric objects in the biological domain have been developed. For novel cell penetration tools, a new process for the micro-fabrication of needle-like structures was developed, with the goal to obtain transparent structures thin enough not to damage the cell.

A very interesting and innovative approach based in the nano-domain was the implementation of scanning probe-actuation techniques using atomic forces. Working simultaneously as a manipulator and a sensing device, SPM tips with attached molecules or cluster of molecules (functionalised tips) were used to scan surfaces or particles and finally working as a nano-gripper.

2.4 Vision and Position Sensors

In order to build a robust and reliable image-based feedback subsystem for the positioning of the robots during the accomplishment of the pre-configured tasks, as well as providing a high-level tool for the analysis and interpretation of scene image information, it was necessary to achieve the objectives shown in Table 2.

Vision represents the principal agent for providing 3D-position information to enable the local control and co-ordination of tasks to be accomplished by the microrobots. In this context, the quality of the vision system was important since it must accurately and reliably capture and process visual data into a form easily and efficiently interpretable to the control system.

The global localisation system is based on a new sensor principle, incorporating computer vision.

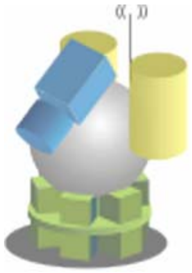
- A sensor system for global localisation to provide information about the absolute position and orientation of the robot(s) operating on the 200 x 200 mm² workspace using at least 5 samples per second per robot and having an accuracy of about 5 µm.	
- A vision sensor to provide on-board imaging capabilities. For this, a miniature CMOS camera and lighting tools have been mounted on a Miniman IV-Robot.	
- A flexible and robust real-time vision system for 3D object recognition and tracking	
- A high-level scene image understanding system to aid system control and robot path planning.	

Table 2: Vision and Position system

Beside SPM tools, high-resolution local sensors based on atomic force microscope probes (AFM) have been developed. One microrobot was equipped with this probe which was able to scan – unlike conventional SPM imaging – a very limited area, sufficient to provide position information. This allows the robots to track micro-structures.

2.5 System Control

The envisaged objectives of the control system are listed briefly as follows:

- Mobility and manipulability motion control is meeting the performance constraints as well as compensating most of the “micro-scale” effects
- Integration of control and sensing at both the low (servoing) and high (supervision) levels
- Collective and co-operative behaviour of the microrobot agents
- Computer-based supervision for on-line motion control and failure handling
- Tele-Manipulation user interface

The system control itself contains all the algorithms to ensure a save navigation of the robots on the working platform. For this, a collision detection algorithm was included. Furthermore, a task planning tool enables the user to control the assembling and experimental phases during the workflow.

3 Methodologies

For the realisation of this challenging project, several methodologies have been examined and realised by the different partners. Very modern and up-to-date manufacturing methods, software development systems as well as new measurement principles like the navigation system, cell manipulation and power supply have been developed. Below, a closer look at the different challenges will be taken to show how these methodologies were included into the development of MiCRoN.

3.1 Slip-stick principle

This motion principle has been examined during the project very detailed. The results of this research can be found in the PhD-thesis written by Arvid Bergander, EPFL, during the MiCRoN project[3]. This principle is used within every actuation of the robot:

- Platform motion
- Rotator movement

Analysing the state of the art at the beginning of the project, this principle has turned out to be the most accurate, fast and reliable. Furthermore, the electronic actuator drivers which have to be integrated into the on-board electronics are not very complicated, so that the hardware integration itself was not a problem.

3.2 Control software

Controlling the Slip-stick movement, several software solutions are available at the moment. A completely new approach has been realised: Using genetic programming and adapting the algorithms to the principle of the Slip-stick movement, it was possible to get a very stable and accurate control tool. Genetic programming together with Slip-stick motion principles has never been used before, so solving this task was a novel methodology developed in MiCRoN.

3.3 Power supply

Because the microrobots used in earlier projects were tethered, it was one of the major goals to overcome tethered solutions and try to go beyond these supply principles. Therefore, a power floor was designed that uses electromagnetic waves for untethered energy transport. Another solution found at the MIT[4] within the Nanowalker-Project is using a power floor as well, but they have the disadvantage of needing direct physical contact between the floor electrodes and the legs of the microrobot. It was already one of the initial ideas to avoid this and to develop a different power floor. The success of this development was documented by a patent application done by the partner responsible.

3.4 Global positioning system

For navigation tasks of these autonomous mobile robots, photogrammetric methods are normally used for the detection of the robots' positions. The resolution of these measurement methods is restricted to 20µm, which is too big for tasks in the micro world or for sensing very small movements of the robots itself. To reach regions of about 5 µm, interferometrical methods must be used. Because two-dimensional movements have to be observed, the

---

[3] Bergander, A.: Control, Wear Westing and Integration of Stick-Slip Micropositioning, EPFL, Lausanne, 2003

[4] Martel, Sylvain M.; Madden, Peter; Sosnowski, Luke; Hunter, Ian W.; Lafontaine, Serge NanoWalker: a fully autonomous highly integrated miniature robot for nanoscale measurements; Proc. SPIE Vol. 3825, p. 111-122, Microsystems Metrology and Inspection, Christophe Gorecki; Ed.

interferometrical method should support at least two dimensions. Furthermore, no external measurement force should influence the movable objects to avoid unwanted effects. The best choice was a Moiré-effect-based interferometer for the main measurement principle because it contains all the characteristics needed for this measurement task. But because this interferometer needs some input parameters for correct position calculation, the combination of photogrammetric and interferometrical measurement methodologies was chosen. This leads to a totally new measurement method, which is documented by a patent.

3.5 On-Board Communications

The IR-based communication principle is successfully used in the MIT Nanowalker project. By increasing the communication speed up to 4 MBit, the information flow would be sufficiently high for solving communication tasks in MiCRoN. With regard to the ASIC module used herein, the physical layer of communication protocol has been specified; it is partially equivalent to the VFIR IrDA standard 1.4. Because of the need for reducing power consumption during biological experiments, the communication protocol has been adapted to provide a slower communication link, too.

3.6 On-Board Electronics

Two different power sources have been considered for MiCRoN driving:

- Low size battery: for stand-by digital circuitry and emergency power
- Power floor: as a main power source for navigation and manipulation

Two different power conversion stages have been defined for the complete on-board electronic system:

- Battery power conversion and battery charger from power recovery system
- 50V power conversion and charge driving module

Three main innovation key points have been proposed:

- Charge driving methodology for higher positioning accuracy
- Power recovery driving system for high yield power conversion
- Charge feed-back position methodology
- Optimal feedback fine position control based on internal model and position estimation.

A set of discrete solutions have been developed and analysed. Several tests have been performed on the MiCRoN robot. The final circuitry is implemented by using microelectronic Integrated Circuit technology (FPGA-technologies)

3.7 Grippers and novel tools

3.7.1 Grippers

At the beginning, some types of micro grippers with different shapes of the grasping areas have been considered. A dedicated model for adhesion forces between object and gripper has been devised. The model takes into account realistic working set-ups in terms of geometry, contact area and environmental conditions.

Experiments with different gripping tools and different micro-objects have been performed and compared with the theoretical analysis in order to extract some guidelines for the design of micro-manipulation end-effectors in the micro-domain.

For manufacturing, wire EDM is normally used for machining 2D shaped grippers, and to manufacture a 3D gripper arm required that the 2D profile of the gripper was first cut out of a mounted piece of stock stainless steel. To realise the 3rd dimension, this cut piece was then mounted at 90 degrees to the first cutting plane, and then the piece was cut from above. Two gripper arms were produced during each cutting cycle. The minimum tip thickness was about 70µm, which is a limitation imposed by the wire EDM machine (diameter of EDM wire=100µm).

3.7.2 Novel tools

Two major novel tools have been developed within MiCRoN:

1. An AFM tool assembled to the rotor actuator of the robots for nano manipulation tasks;
2. A Syringe Chip assembled to the rotor for biomedical cell manipulation tasks.

3.7.2.1 AFM-tool

For the realization of the AFM-tool, piezo-based actuators have been used because of their high resolution. This is a common method at the moment in this class of nano-measurement and nano-handling equipment. The design is simple but very effective:

- The designed and implemented AFM tool consists of two parts: sensor and actuator. The sensor is a commercial piezo-resistive AFM probe, which is connected to the actuator by means of a special holder developed by EPFL. The actuator is a multilayer piezoceramic element, which can be moved in three orthogonal directions.
- The actuator consists of four piezoelectric stacks (dimensions: 2 × 2 × 3, 5 mm^3) allowing the position control of the AFM tip with a resolution in the range of nanometres. The piezo-actuator acts as a bimorph but the partition into four independent elements, makes them three-axial, moving in X and Y directions (for making scanning experiments) and in Z direction (for making nanoindentation experiences).

3.7.2.2 Syringe Chip for biomedical cell manipulations

The micro fluidic Syringe Chip integrates monolithically a micro needle, a thermo pneumatic micro pump connected to this needle, and a sensor. The micro needles as well as the area around the micro needle are made of translucent materials (silicon dioxide, glass). Filling of the chip is done by simply dipping the needle into the fluid to be injected. In contrast to commercially available injection systems, the size of connecting tube and pump of the syringe chip is adapted to the volume to be injected. Once filled, the chip can be used to perform several hundreds of injections. The injection volume can be adjusted and controlled very precisely. Power consumption of the SyringeChip is less than 2 mW for injection of up to 2 pl of liquid and the integrated actuator can be controlled by a PID-controller or even a pulse-width-Modulated signal. The realized micro-needle has an outer tip diameter of 2 µm and a length of 25µm.

4 Project results and achievements

In this chapter, a short overview of the results achieved is given. During the work progress from the start of the project over nearly four years of development, the consortium repeatedly refined the specifications of the final demonstrations. The main contributions of the MiCRoN project are its micro mechatronic components:

1. **Power floor** and untethered power supply
2. **Positioning sensing system** that provides position data of the robots within a resolution of 5 µm to the control software. It is completely integrated into the control software
3. **Control software**; closed loop robot-moving status has been achieved with MiCRoN as well as with Miniman robots.
4. **Piezo Drives** working with 20 V power supply and with a resolution of 2 nm;
5. **Rotatorial actuators** with a resolution of 0,15 µrad
6. Several **micro tool tips** which are able to handle micro parts down to 20µm in size; fixed at the robots rotatorial actuator
7. A **Syringe chip** which enables the user to handle and to manipulate cells; fixed at the robots rotatorial actuator
8. An **AFM tip for scanning surfaces** within the nano range; the AFM tip is fixed at the robots rotatorial actuator
9. **Task simulation** and **task planning** via complex and user-friendly GUI.

4.1 Comparison with initial project objectives

The following table gives an overview over the realised results compared to those that have been initially aspired:

Robot Platform		
Project objective	**Proposed**	**Realised**
- ***Size (cm^3)***	10mm x 10mm x 10mm	12mm x 12 mm x 12 mm
- ***Locomotion***		
resolution	Several nm resolution	2 nm resolution; 0.15 µrad rotatorial resolution; 20V supply voltage for piezo actuators; new piezo manufacturing process developed
holonomic motion	X-, Y-Directions, rotation	+X, +Y, rotation
speed	Several mm/s	0.2 mm/s
- ***Communication***		
Comm. with host computer	Planned	Realised, 4MBit IR transmission channel
Comm. With other robots	Planned	Not realised
- ***On-Board Power Management***		

Rechargeable Battery	On-Board battery, 10 min. duration	3s power supply duration – not realised because of too high energy consumption
Powerfloor	Supplying all robots within an untethered environment	Only one robot can be supported because of a too high onboard energy consumption

Novel Tools

Project objective	Achieved	Realised
- ***Gripper***	Gripper with additional rotational upright DOF, fixed at the robots actuator	Realised
- ***Novel Tools – Syringe Chip***	Handling of biological parts like cells, fixed at the robots rotator actuator	Realised
- ***Novel Tools –*** - ***AFM-Tip***	Scanning of nano surfaces, fixed at the robots actuator	Realised

Vision and Position sensors

Project objective	Achieved	Realised
- ***Vision system***		
On-Board CMOS-Camera	Planned and proposed	Realised; complete actuated lens system
Vision Software	Planned and proposed	Realised and running
real-time vision system for 3D object recognition and tracking	Planned and proposed	Realised and running
- ***Global localisation system***		
Resolution	Resolution = 5µm	Realised, Resolution = 4,5µm
Working Area	Working Area = 200mm x 200mm	Realised, Working area = 300mm x 200mm; max. possible area 410mm x 315 mm
Robot Orientation	Measuring of the robot orientation	Realised (Control system)
- ***SPM-Tool***		
On-Board AFM	On-Board AFM, assembled at the rotatorial actuator	Realised and partly running
Probe tracking	Tracking of probes	Realised

System Control

Project objective	Achieved	Realised

- ***Mobility and manipulability motion control***	Possible for each robot including sensor monitoring of each robot	Motion possible, onboard sensor monitoring not realised caused by the absence of robot sensors
- ***micro scaling effects***	Control of micro-scale effects	Partly realised with the gripper tool
- ***Low and high sensitivity levels***	Control low (servoing) and high (supervision) levels	Realised
- ***Collective and co-operative behaviour***	Possibility of communication between each robot using the host computer	Not realised
- ***Computer-based supervision***	on-line motion control and failure handling	Realised
- ***Tele-manipulation user interface***	intuitive user interface	Realised in system simulations

4.2 Relations and synergies with other relevant projects

The MiCRoN project took benefit from synergies with the following projects:

1. The MINIMAN-Project already finished in January 2002; the development of micro-robots equipped with tools, navigation system and a control system gave the foundation for the development of the new generation of MiCRoN robots. The MINIMAN robots have been used as a test platform for the new localisation system and closed loop control software development. By analysing the weaknesses of the MINIMAN robots, the new MiCRoNs are working untethered, with higher precision and are equipped with novel tools that cannot be found in MINIMAN robots.
2. The I-SWARM project depends partly on the results of MiCRoN like position sensing, tool drivers and communication via IR. Furthermore, the EU asked the consortium to use the results of MiCRoN to improve the I-SWARM investigations coming up during this project.
3. A proposal to the DFG has been written in German language to improve the possibilities of the positioning system to 3D real-time high precision measurements. The acknowledgement of this proposal is awaited in spring 2006.
4. EPFL have been involved in the submission of three new EU projects related to MiCRoN. One of them will be accepted (GOLEM: bio inspired assembly process for micro- and nano- products, FP6-2004-NMP-TI-4). The other one had the hearing at the end of November (Nanohand: Micro-nano system for automatic handling of nano-objects, FP6-2005-IST-5).

4.3 Implications for the EU policies and standards

Basically, the results out of the MiCRoN project will encourage the development of highly miniaturised microsystems. Researchers dealing with micro- and nano-structures will get a flexible and easy to use tool for handling tasks. Both the tool itself and the knowledge gained will give European industry and research a strong potential for realistic competition with the USA and Asia.

4.4 Benefits to the society

4.4.1 Enhancement of the European competitiveness in the microrobotic research area

Due to the extensive nature of this project, a wide range of expertise was required in fields such as robot design, actuation principles, powering, wireless communication, sensors, machine vision, robot control and co-ordination and thus a large consortium was necessary. This range of expertise cannot be found at a national level. The innovation of the project was met by the collaboration of European researchers who are amongst the leaders in their areas. In this way, all participating countries will benefit from the results of the project. As expertise in microrobotics related areas in Europe is limited to a restricted number of research groups, it was clearly beneficial to join forces and concentrate on a common, ambitious project.

4.4.2 Future growth of the European industry

Microsystems and nano-technologies are more than ever in rapid development and are increasingly expanding into other key technological areas – mainly the biological research area. Various other markets for different types of microsystems, *e.g.* automotive industry, medicine, environmental protection, biotechnology, avionics, consumer electronics, telecommunication, production and process engineering, offer a lot of research fields, and the results out of MiCRoN will help the European research community to reach more goals in the mentioned areas.

4.4.3 Quality of life

Looking at the results - for example regarding the syringe chip - developed during this project, the benefits for the biomedical research area are clearly visible. By using this tool together with an autonomous robot and the vision system, biomedical researchers are more flexible in handling, penetrating and manipulating cells under a local microscope. This leads to a higher efficiency for the development of new medical drugs.

Other terms of improving the quality of life will be the ability of handling meso-scale parts during the micro system prototyping process. This decreases the time-to-market value as well as the costs during the development of microsystems.

Therefore, MiCRoN mainly has an indirect impact in medicine and health care. The result of the project – the microrobot cluster – provides a unique tool, which enables both a further miniaturisation of existing components and the design of completely novel and innovative products. Microsystems play an increasingly important role in medicine, particularly in terms of implants, minimally invasive medical procedures and new forms of reconcilable physical examinations. Minimally invasive procedures for both diagnostics and therapeutics have generated much attention for their ability to reduce patient pain, hospital stays and treatment costs. For example, endoscopes are becoming smaller due to the advances in MST.

5 Selected Project Results

In the following sub-chapters a collection of selected and most interesting results will be presented. For a closer look to all results, please refer to the detailed annual reports of the MiCRoN-project.

At the end of this document, a list of the most recent publications and papers is given to the reader for more scientific results of the project. Last but not least, the project home page can be visited for more information.

5.1 Integrated micro manipulation actuators

The rotational drive have been developed, evaluated and redesigned to be a suitable interface between robot and tool. Five rotational drives with specific rotors for each tool have been delivered. Furthermore the rapid prototyping technique for making multilayer piezoceramics, developed in the beginning of the project, has been utilized to make the drivers for the grippers developed by the consortium.

Most of the development and evaluation on drives before the last project year have been performed with focus on the locomotion module. After selecting the quasi-static walking actuator type for the rotational arm and not for the locomotion unit, most efforts have been on refining and optimising the design of the micromanipulation module for integration on the final robot, but the rotational actuator performance has also been thoroughly evaluated.

In the rotational actuator, three identical bimorphs are arranged in the tangential direction of a circle requiring only 2 drive signals at low voltage. Together with the monolithic approach this fulfils the aims of having simple driving and assembly. Actually no assembly is necessary for the actuator itself and it is easily fabricated at low cost and in large series.

The rotational actuator, the stator, is mounted on a printed circuit board and an arbitrary tool can be integrated directly onto the rotor that is held in place by a steel spring. The rotational actuator can generate a pure rotation and a pseudo translation of different tools using a quasi-static walking principle, see Figure 5.

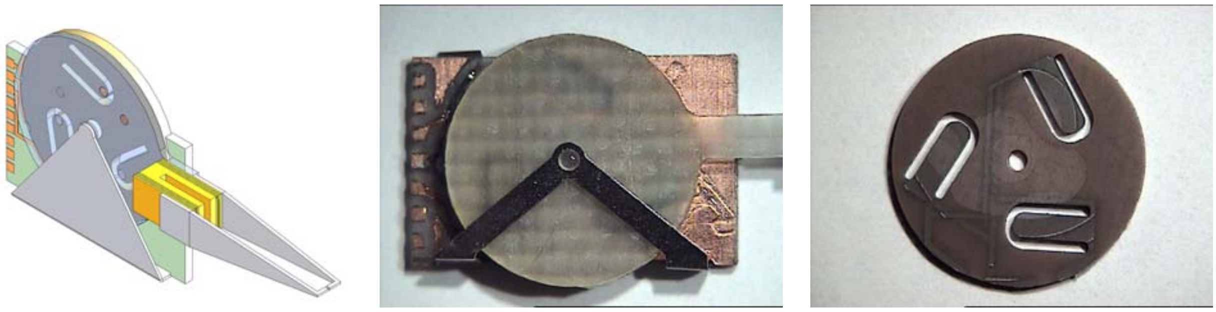


Figure 4: Micromanipulation module with rotational actuator (∅ 9.2 mm) mounted on printed circuit board with tool (gripper) integrated directly onto the rotor (left). Micromanipulation module without tool (middle). Rotational actuator (right).

The maximum torque of the motor is 80 µN at a drive voltage of 50 V and a spring force of 1.2 N. The rotational actuator has extremely good motion resolution (0.1 µrad) for driving frequencies up to about 80 Hz (0.1 rpm). Fast transport can be achieved in the frequency range 3-6 kHz (4 rpm). The power consumption is about 1 mW and 80 mW respectively.

The rapid prototyping technology for making multilayer piezoceramics that has been developed by DMS during the MiCRoN project has not only been used to fabricate the rotational actuator, but also for making the drives/actuators for the grippers.

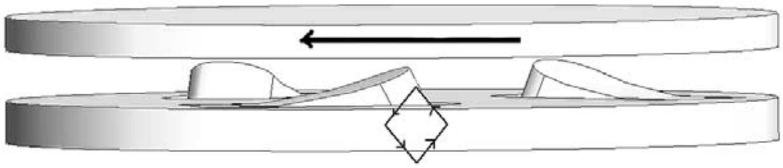


Figure 5: Schematic description of the rotational actuator. The bimorph tips move along the indicated trajectory moving the rotor clockwise in a stepwise manner.

In the monolithic structure, two multilayer unimorphs are connected at one end (see Figure 6). Depending on the placement of the electrodes normally closed and normally open gripper were fabricated. Three-axial multilayer piezoceramic drives/actuators originating from the preceding Miniman project has also been supplied, which are used for the AFM scanning tool.

Figure 6: Normally closed gripper actuator (left). Gripper arms are assembled to the piezoactuator to magnify the stroke (right).

5.2 Gripper Tools

The possible configuration principal of a traditional gripper looks like shown in Figure 7. The new micro gripper is composed by:

- supporting needle
- piezoelectric actuator in bimorph configuration
- Two gripper tips

The gripping functionality is ensured by the inflection of the Piezo-actuator due to the applied driving voltage (Figure 7 a + b).

A micro-gripper was developed which consisted of a piezo-electric actuator (developed by DMS) with gripper arms of stainless steel machined by wire EDM (Electro Discharge Machining). Although in this work, u-shaped actuators were used for the steel grippers, in theory bar shaped actuators could also be used.

The stainless steel gripper tips are as shown below and were machined using wire EDM. The total gripper length is approximately 12mm and the tip thickness of the gripper is approximately 60 µm.

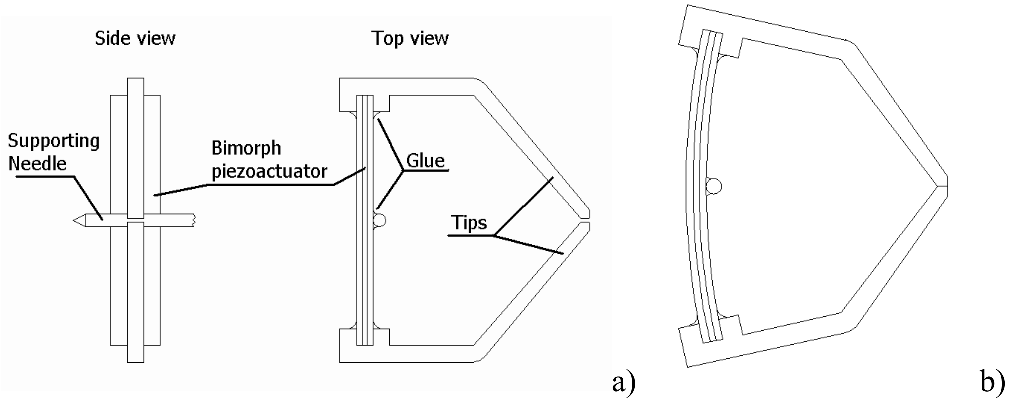


Figure 7: Gripping Functionality

Wire EDM is normally used for machining 2D shaped, and to manufacture a 3D gripper arm required that the 2D profile of the gripper was first cut out of a mounted piece of stock stainless steel. To realise the 3rd dimension, this cut piece was then mounted at 90 degrees to the first cutting plane, and then the piece was cut from above. Two gripper arms were produced during each cutting cycle. The minimum tip thickness was about 70um, which is a limitation imposed by the wire EDM machine (diameter of EDM wire is 100µm) - if the tip is smaller, the arc sparks around the smaller geometry, and the cut surface quality deteriorates.

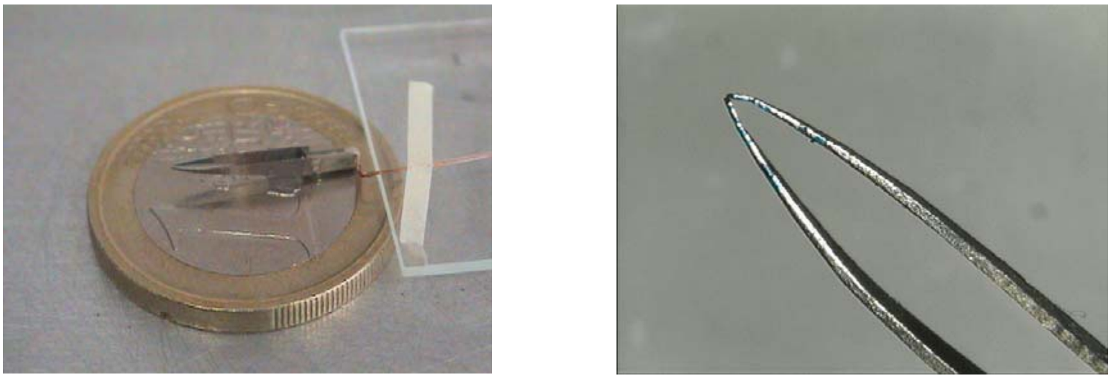


Figure 8: Different view of a gripper tool

Once these stainless steel gripper arms were cut out, they were glued to the piezoelectric actuator. The glue was used sparingly to ensure that it does not spread over the sides of the actuator, causing a restriction of the bending. To align the gripper tips, one needs to use slow curing glue so that the gap distance of the tips can be adjusted if necessary.

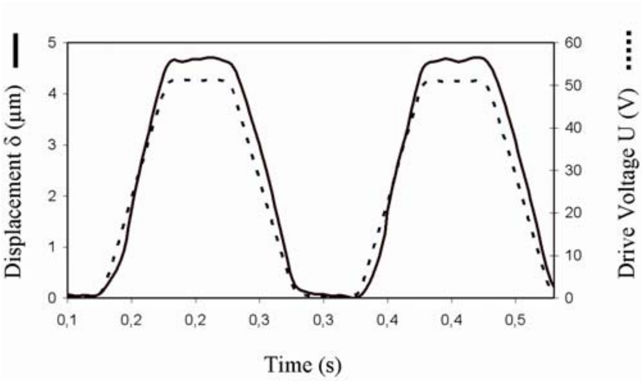


Figure 9: Characterisation of the gripper tip displacement

The characterisation of the gripper tip displacement (with voltage and time) is shown in Figure 9.

The final step necessary was to attach the gripper to the rotor. This was again done with epoxy glue with a 20 minute pot life to ensure that adjustments could be made. Further to the manufacture of these grippers, several marking schemes were designed to enable machine vision for tracking of the grippers, including marking by polymer ink dots and FIB (Focus Ion Beam) shape machining (see Figure 10).

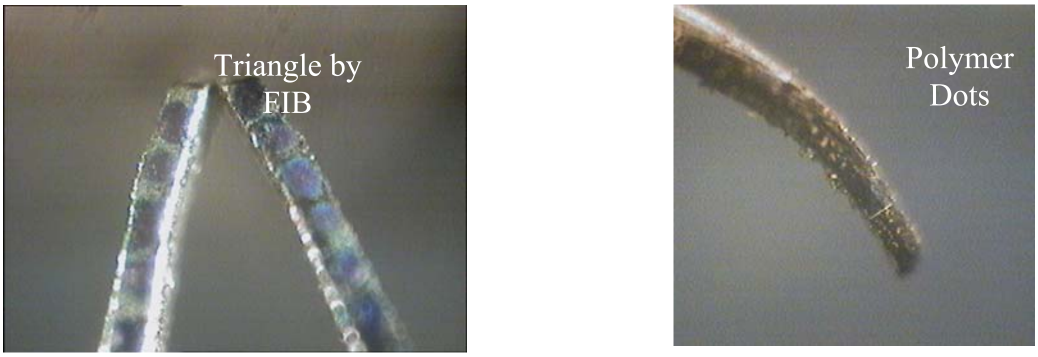


Figure 10: Marking the gripper tips with polymer ink dots

5.3 Integrated micro tools for biological and biomedical Nano manipulations

5.3.1 AFM-Tool

5.3.1.1 New Silicon Tips development for AFM

FIB-sharpened AFM probes have been fabricated to be used to characterize nanostructures. The FIB apparatus is used to mill a ~1.5 □m long needle-like protrusion from the end of a commercially available cantilever [NCH AFM probe, Nano Sensors, Switzerland]. The protrusion has a point diameter of ~10 nm and an angle at the point of 15° compared to the original AFM probe which has a point diameter of 10 nm and an angle at the point of 60°. This modification does not affect the resonant frequency of the AFM probe, but allows the probe to examine the inside of the nano patterned structures in more detail that using standard tips.

To test the sharp AFM tips, there have been used 5x5 nanowell structures imprinted in PMMA. The walls of the wells are 100 nm wide and enclose square wells which have an area of ~100 nm^2

5.3.1.2 AFM Characterization

FIB-sharpened AFM probes have been fabricated to be used to characterize nanostructures. The FIB apparatus is used to mill a ~1.5 µm long needle-like protrusion from the end of a commercially available cantilever [NCH AFM probe, Nano Sensors, Switzerland]. The protrusion has a point diameter of ~10 nm and an angle at the point of 15° compared to the original AFM probe which has a point diameter of 10 nm and an angle at the point of 60°. This modification does not affect the resonant frequency of the AFM probe, but allows the probe to examine the inside of the nano patterned structures in more detail that using standard tips.

Micro fabricated cantilevers are mechanical sensors, which are used in AFM to measure interaction forces with high resolution (1pN). For cell measurements, soft silicon nitride cantilevers are commonly used. The methodology used is a silane-based compound. We have experimentally investigated the effect of chemical surface modifications of Si3N4 using several silylating agents.

One of the main problems to integrate nanotools in small robots is the energy required to perform the manipulation process. One possibility is to use the energy used in the displacement of the robot to perform simultaneously a handling or manipulation action. For instance, one possibility is the use of small rakes as main unit to produce filter systems that can be used to separate or remove cells or sub-micron structures.

Polymers show themselves to be excellent candidates for the production of biomedical devices incorporating nanometric systems. Low fabrication costs, fast design realisation times, optical transparency, good sealing properties, and, most importantly, biocompatibility, are all advantages that can be plundered by scientists for the production of such devices. Here we present the patterning of polymer surfaces with nanometric channels, posts and wells for use in the development of filter systems

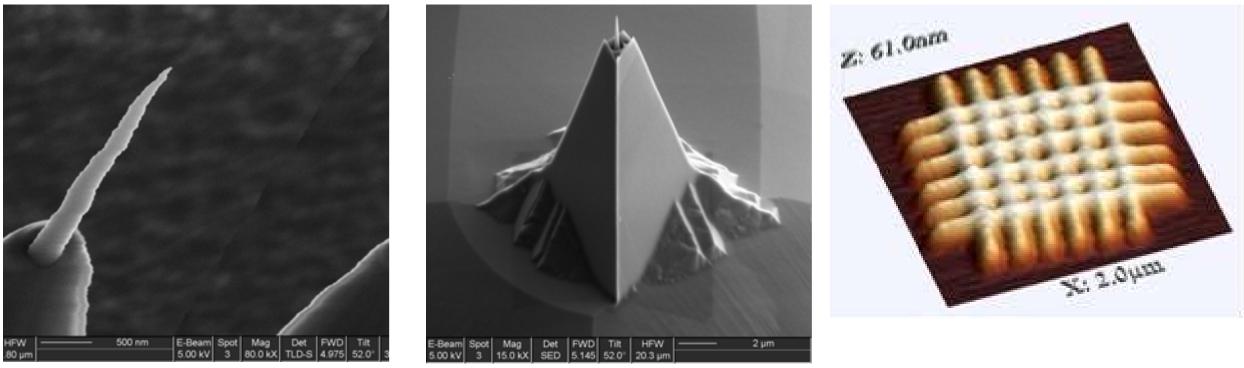


Figure 11: Different Nano tip shapes

5.3.2 Micro-Machined Syringe Chip for Cell Penetration

5.3.2.1 Principle of Work

Micromanipulation of living cells such as injecting synthetic molecules, peptides and proteins, and nucleic acids into the cytosol is an appreciated and powerful technique in cell biology. In general microinjection is realised by treating cell by cell with a pulled glass capillary. The equipment has to reach at least the range of a typical cell size.

The cells used in here are human leukaemia cells (type HL-60) with a typical diameter of 15 μm. The maximum amount of liquid that can be absorbed by a cell is less or equal 10 percent of the total cell volume [1]. So the quantity to be transferred is in the range of 0,1 picolitres. The needle used for injection must have an outer diameter of less than 1μm. Considering that biological material is treated, the transferred liquid has to be well tempered. The power consumption of the whole system should be predictable and must not exceed 100 mW. To fulfil these boundary conditions different models representing partial parts of the whole micro fluidic SyringeChip are set-up. Using these models the whole chip is geometrically designed, consisting of mainly three parts: actuator, micro fluidic channels and needle (see Figure 12).

5.3.2.2 Characteristics of the Micro fluidic Channels and Needle

The parameters for the thermal oxidation process are determined using Matlab^{TM}. The results of the model's simulation and the geometrical boundaries determine the parameters to be used, like oxidation type: wet, temperature T=1000°C and oxidation time t = 1,5h. Using these parameters will lead to an oxide thickness of about 230 nm in the trench and 500 nm on the planar wafer surface.

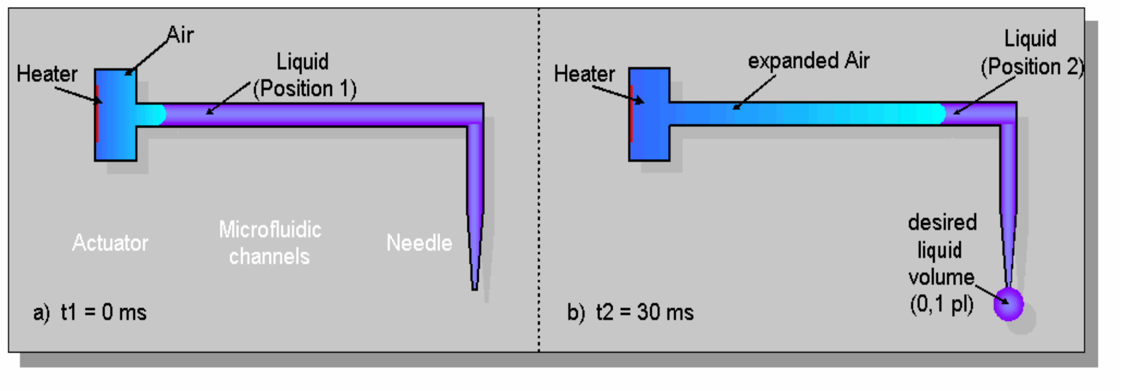


Figure 12: Principle of the micro fluidic SyringeChip

Comparing these calculated values to first experimental data (see Table 3); the validity of the generated theoretical model can be proven.

Thermal Oxide	Theoretical	Measured
Wet		
Plane	504 nm	500 nm
Trench (0,5 µm)	210 nm	250 nm
Dry		
Plane	277 nm	300 nm
Trench (0,5 µm)	265 nm	300 nm

Table 3: Measured and calculated thermal oxide thickness.

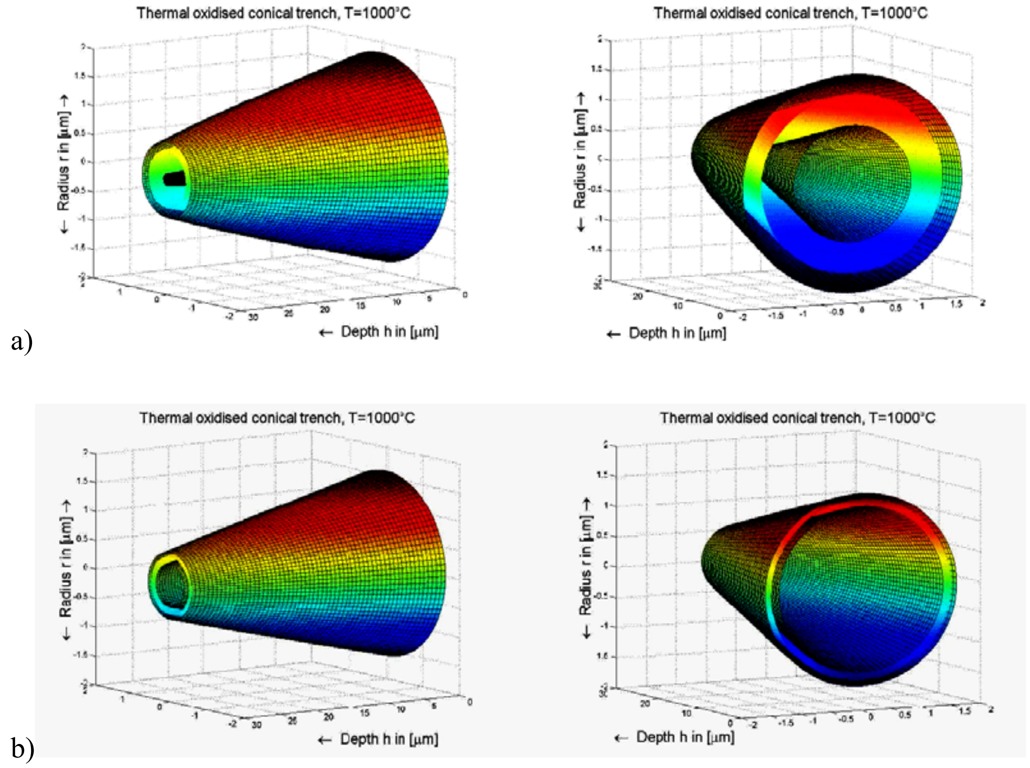


Figure 13: a) profile of dry thermal oxide after 100 h and b) profile of wet thermal oxide after 1.5 h of processing. The oxide boundaries (screened) and the original surface are shown.

Deriving the equations shown in the former chapter in Matlab^{TM} also a three-dimensional model of the conical needle can be generated.

This is done by calculating the corresponding oxide thickness for a certain trench diameter, repeatedly for discrete steps over the conical needle shape. By joining the single results a three-dimensional SyringeChip-Needle is generated (see Figure 13).

The outer dimensions of this simulated needle are 1 µm at the tip and 3 µm at the base of the shape, its length or depth, respectively, is 20 µm.

The electrical power, to dose very small amounts of liquid with the integrated, membrane-less thermodynamic actuator, based on the geometrical requirements for needle and channels, is calculated. The process parameters for thermal oxidation of silicon are derived by combining common and specialised theories on dry- and wet-oxidation. The dry oxidation method is not used – even if the oxide thickness in the planar case is much closer to the one in a trench – because of the long process time, causing a high stress in the whole wafer.

5.4 Position Sensing System

One project goal was the development of a position sensing system with a resolution of about 5µm. This has been successful realised and works now in a stable prototype status. A partly-virtual Moiré-based interferometer was developed to reach this destination.

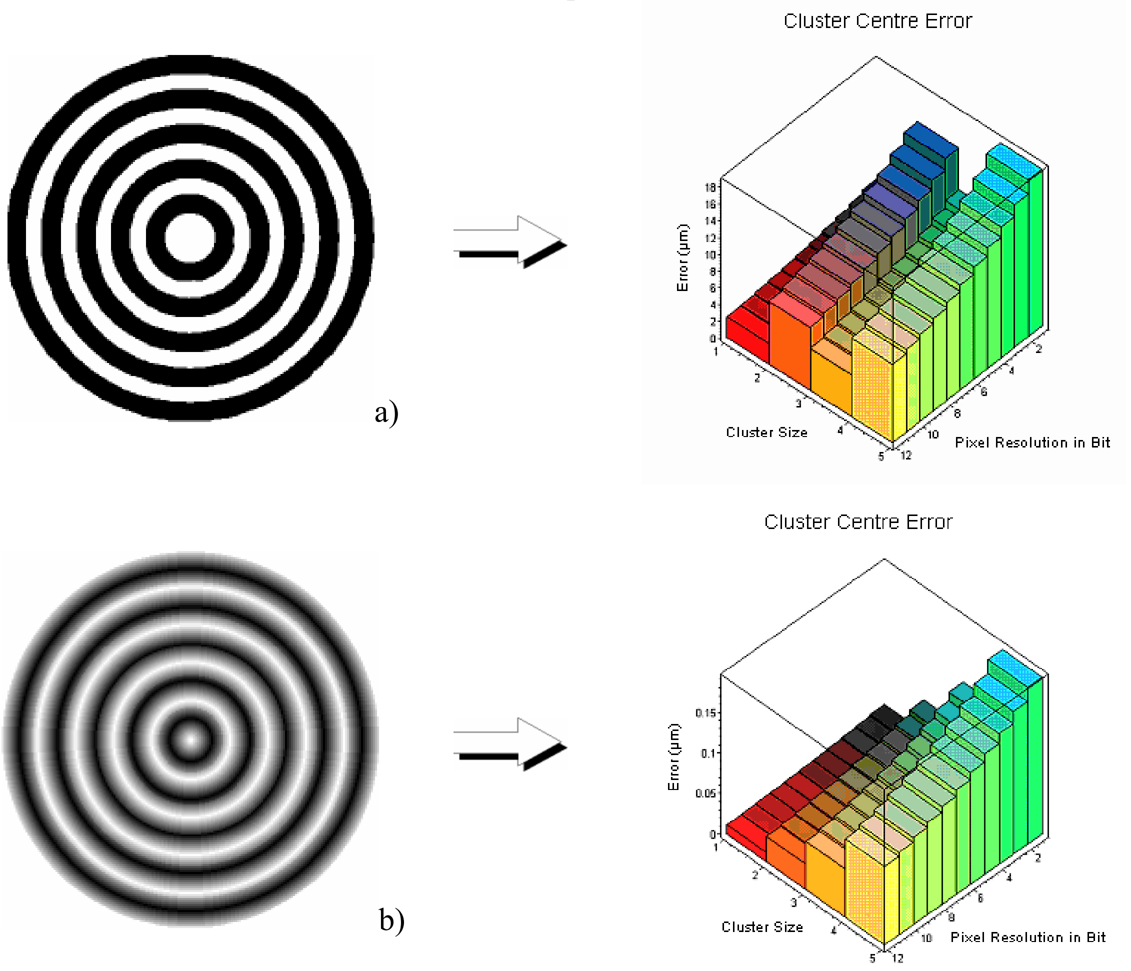


Figure 14: Influence of the different mark shapes on the measurement error (above: hard shaped grating, below: cosinusodial shaped grating)

This measurement tool is needed to get the precise position of the microrobots. Therefore, a simulation was developed first to check if the Moiré-based principle is working within a sufficient resolution. About 60 models of the system with different scenarios has been coded. The main simulation results are:

1. There must be used “blurred” mark grids; that mean that the borders of the several grids are not hard, but cosinusodial shaped (see Figure 14 b). This makes the measurement much more exact.
2. The resolution of the camera system influences not only the resolution, but also the size of the mark: the bigger the resolution of the camera (pixel- and greyscale resolution), the smaller the mark has to be (without loosing accuracy).
3. Because we have a geometrical superposition, formulas of the analytical geometry can be used (including the intersection of circles, because we have circular gratings). The intersection points – the so called Moiré-Points – are nothing else than pixel clusters in the CCD-Image. The analysis of those clusters – mainly the error behaviour – was done using Maple, a mathematics and computer algebra software package.

The software communicates via TCP/IP with the robot control software and sends the coordinates of the Moiré-marks.

5.4.1 Realisation

The position sensing system has now a status of a real-time capable measurement system which is controlled by the user over a GUI and is remotely controllable by the robot control software running on another computer. The synchronization is done via TCP/IP (see Figure 16).

The successful real-time integration is done using so called “Regions of interest” for every measured Moirémark. Once the tracking of the MiCRoN robots equipped with those Moiré-marks has been done by analysing the complete scenery continuously, we now use only one initial detection phase. During this detection phase, the Moirémarks will be detected. After the detection phase is finished, a ROI is placed around the detected Moirémark (see Figure 17). In further measurement cycle only this ROI will be investigated and updated.

One test setup for the measurement system in a real environment that contains optical obstacles is shown in Figure 15 (left). There are several objects in this image:

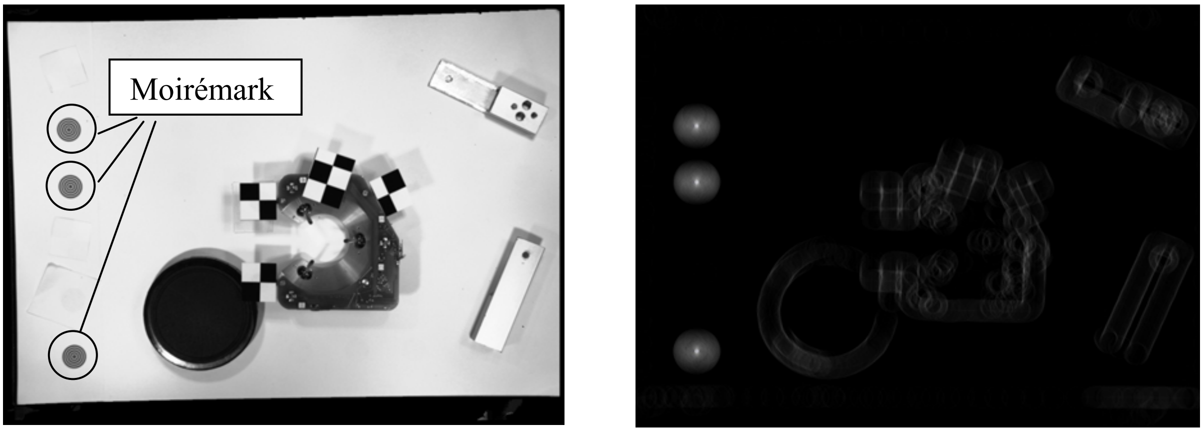


Figure 15: Test image with several disturbing objects; right image shows the filtered measurement image

- Microrobots with equipped Moirémarks
- Chessboard-like distortions on the working floor
- Other black objects which do not belong to a microrobot.

These objects have to be distinguished from the Moirémark, so that a successful measurement cycle is guaranteed (see result in Figure 15 right).

If we analyse this image regarding the Moirémarks, we will get a lot of distortions caused by the objects which are in the image beside the Moirémarks. The measurement result of this during the detection phase is not really satisfying: beside the wanted Moirémarks with their desired Moirépoints, there are also so called "Ghost Moirépoints", which are interpreted as real Moirépoints and finally as Moirémarks. This leads definitely to incorrect measurements.

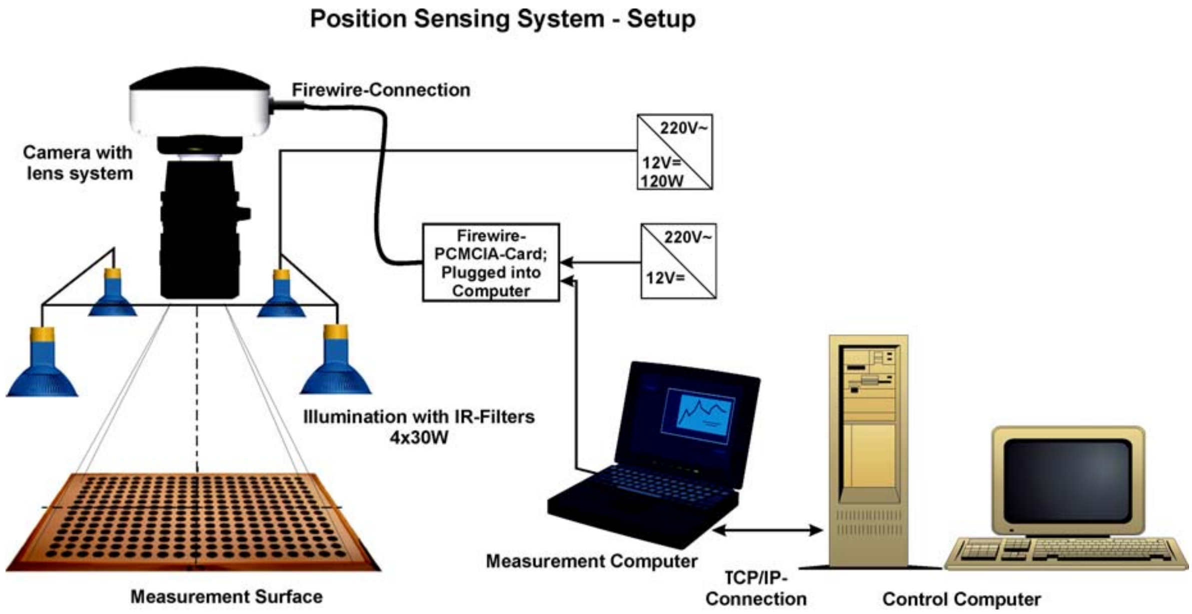


Figure 16: Setup of the Communication model between Position Sensing System and Control Computer

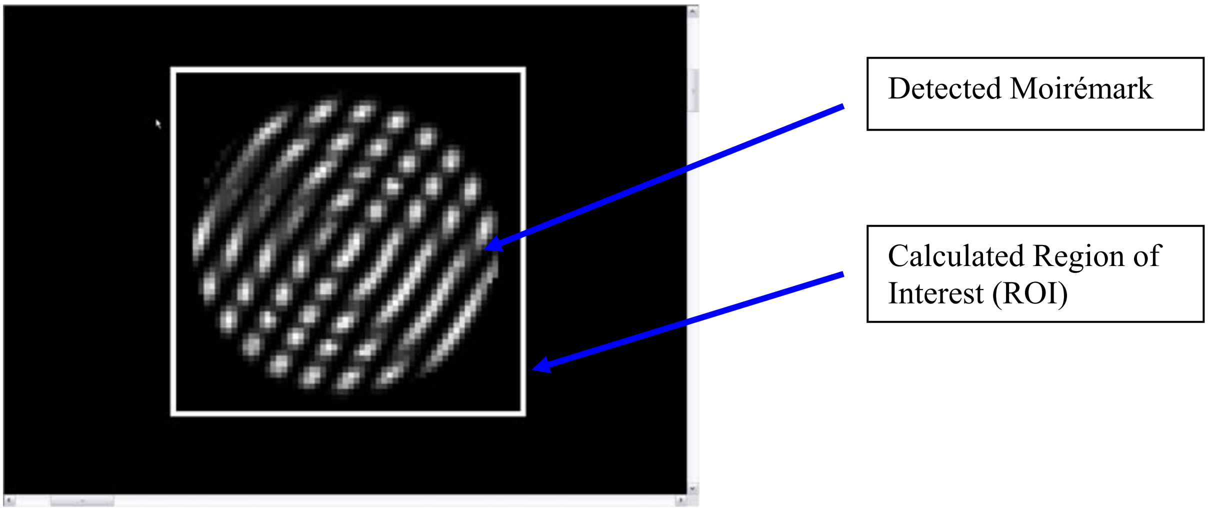


Figure 17: The calculated Region of Interest (ROI) at the detected Moirémark

Because of this behaviour, a mathematical filter has to be introduced into the image processing. As a good possibility, a so called Tenengrad-Criterion is able to separate those unwanted distortions. This filter is placed between the original image and the Houghspace procedure needed for pre-estimating the centre of the Moirémarks.

To decrease the measurement error, we have to increase the number of Moirépoints measured at each Moirémark (refer to Figure 18) for a better result regarding the statistical error, as seen in Figure 19.

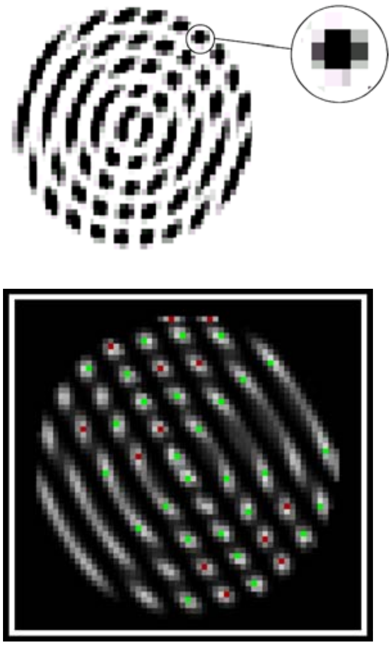


Figure 18: Moirémark with Moirépoints

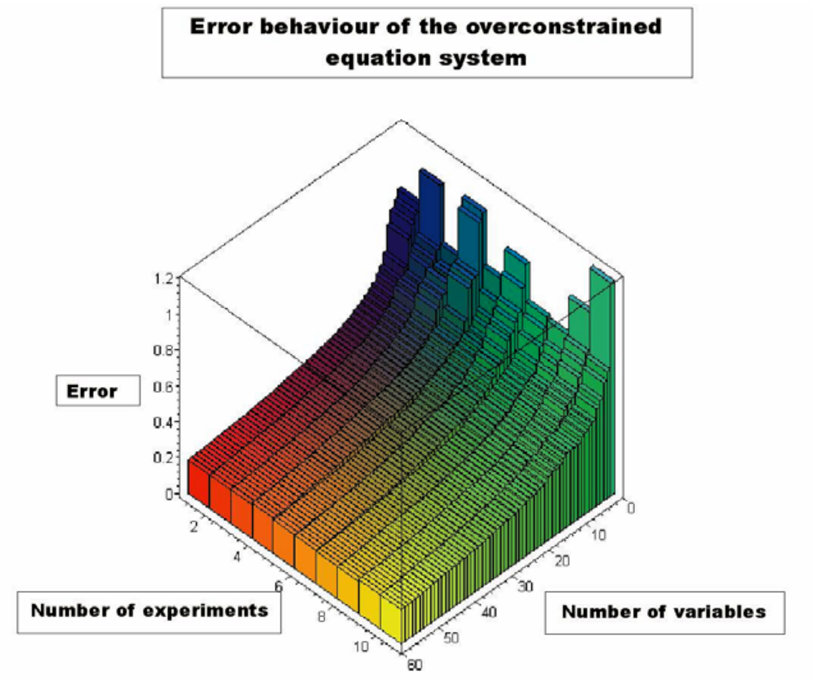


Figure 19: Error behaviour of the equation system responsible for calculating the centre of the Moirémark out of the Moirépoints

In Figure 18 the different kinds of Moirépoints are coloured red and green. The red ones are out of the tolerances given for the point recognition algorithm, the green ones are within the tolerances and therefore usable. The number of the green Moirépoints is quite small because of optical and calibration failures. Therefore it would be helpful to have a higher number of Moirépoints, because a high number of points recognized in the measurement snapshot results in a lower measurement error.

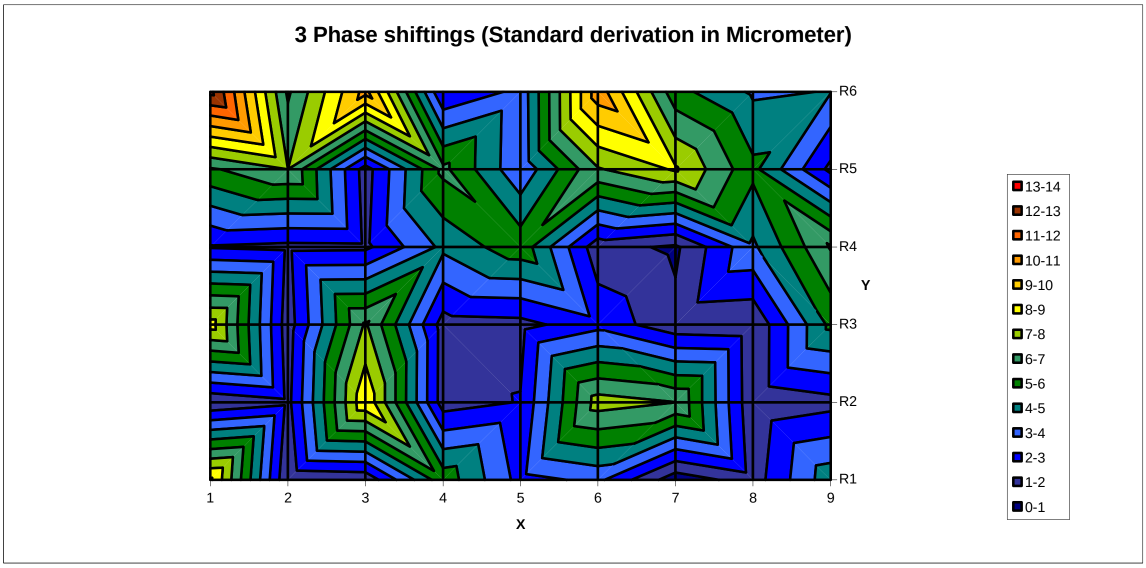


Figure 20: Statistical measurement error using phase shifting (4,2µm)

A good practice for increasing the measurement quality is the usage of phase shifting, as described in several scientific papers. A four phase shifting method has been used. The result is an error surface which shows a statistical measurement error of about 5 µm (see Figure 20). The measurement time for one Moirémark is about 30ms with common hardware.

5.5 Vision-Based Sensor System

5.5.1 Camera system

Due to the specific spatial resolution and optical requirements imposed by the specifications of the MiCRoN demonstrations as well as the camera system itself, an off-the-shelf solution was not available. Therefore, it was decided to design and build the camera system within the Consortium taking into account, as much as possible, all the physical constraints and the desired features needed by the vision subsystem.

The camera is based on the Panasonic GP-CX261 colour CCD 1/4" camera module and a customised lens that has been modified to achieve a magnification of about ×5. With this camera, it is possible to see objects as small as a few µm. The maximum resolution achievable is about 1 pixel/µm. The working distance, *i.e.* the distance between the lens and the object, is in the range of 4-5mm.

The mechanical design was subsequently modified to address the need of electronically moving the camera tip (the part holding the lens) with respect to the fixed CCD imaging chip. This is a requirement for the depth from defocusing technique used for 3D depth estimation, which builds a depth map from a stack of images taken at different heights. The new design of the camera is shown in Figure 21. With this design, it is possible to move the part holding the lens by exciting the two coils integrated on the camera tip body. The range of movement is about ±1.2mm around its neutral position.

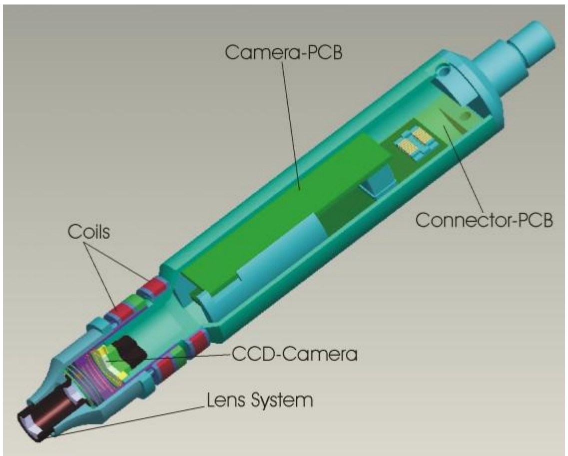


Figure 21: Second prototype of the on-board camera system.

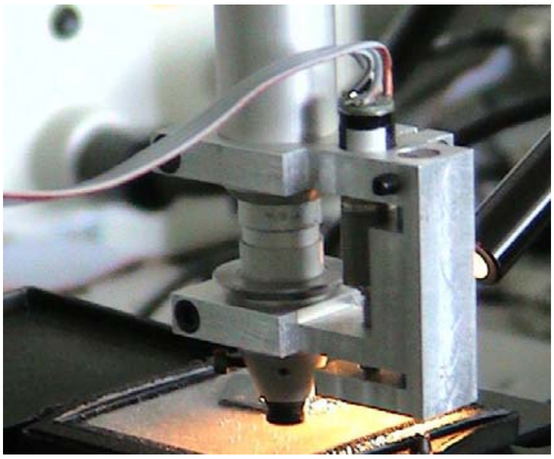


Figure 22: Third prototype of the on-board camera system.

As a consequence of new object recognition and tracking algorithms being investigated and tested for suitability to the MiCRoN demonstrations, it was necessary to yet modify the design of the on-board camera to provide a mechanism for moving the lens linearly within a certain range, rather than just 3 fixed positions. The reason for this modification will be clearer after the section regarding object recognition (see chapter 5.5.3).

Therefore, a third camera prototype was conceived. This has a very small two-phase stepper motor and gearhead assembly (Arsape AM0820-2R-V-3-18-08-E150A) that is mounted vertically next to the lens holder. The motor has two phases and an 18° step angle (20 steps per revolution). The gear head is a planetary type with a ratio of 16:1 and a backlash of less than 3°. This backlash can be compensated by adding a fixed extra number of steps to the motor command. An aluminium bracket made in-house allows the translation of the rotational motion of the motor shaft into a linear (vertical) motion of the lens holder.

The stepper motor is controlled by an external controller board, which can receive commands through the parallel port of a PC. A simple GUI program was therefore developed to facilitate the testing of this motor assembly.

5.5.2 Carrier robot

Because of the final size of the camera system, it was decided to use the MINIMAN-IV robot as its carrier and, for this reason, the robot and the camera will be tethered. The design of the robot has been slightly modified to accommodate the camera in a vertical position. Because the camera's depth of focus is very limited, it is important that the object is seen from the top (vertical) to ensure that the whole object is in focus.

Figure 23 shows an impression of the MINIMAN-IV robot with the camera mounted on it.

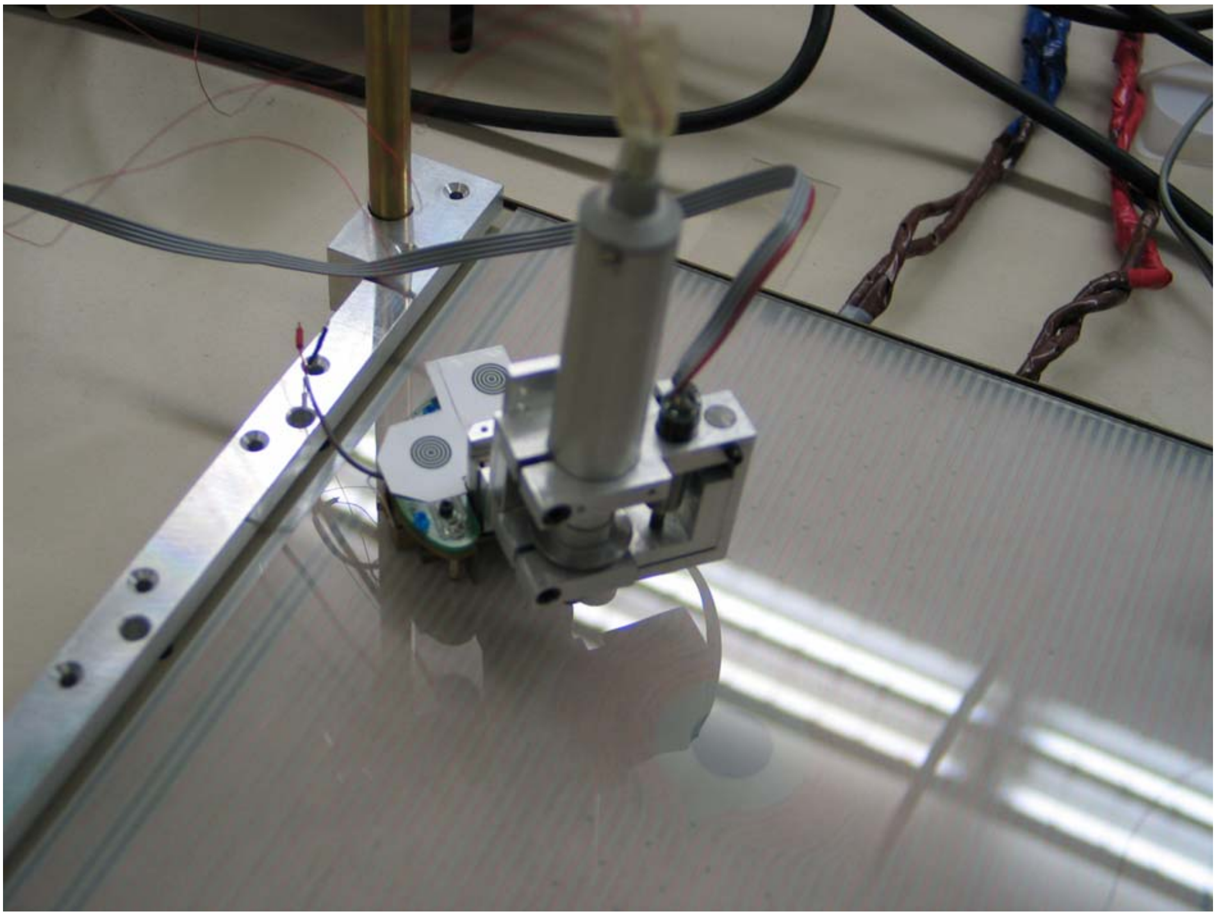


Figure 23: Miniman IV-Carrier robot with camera

5.5.3 Object recognition

During the course of the project, a number of computer vision methods for object recognition have been investigated, implemented and tested. To do this in 3D, a way to calculate object depth has to be devised. There are generally two ways to deal with depth: depth from stereo and depth from focussing or defocusing. However, in the context of the MiCRoN environment, stereo techniques are not feasible because of the physical constraints imposed by the system that is the size of the objects, the size of the camera and the camera working distance. Thus, in these circumstances, the only feasible approach to estimate the depth of an object from a monocular camera system is the depth from focussing/defocusing technique.

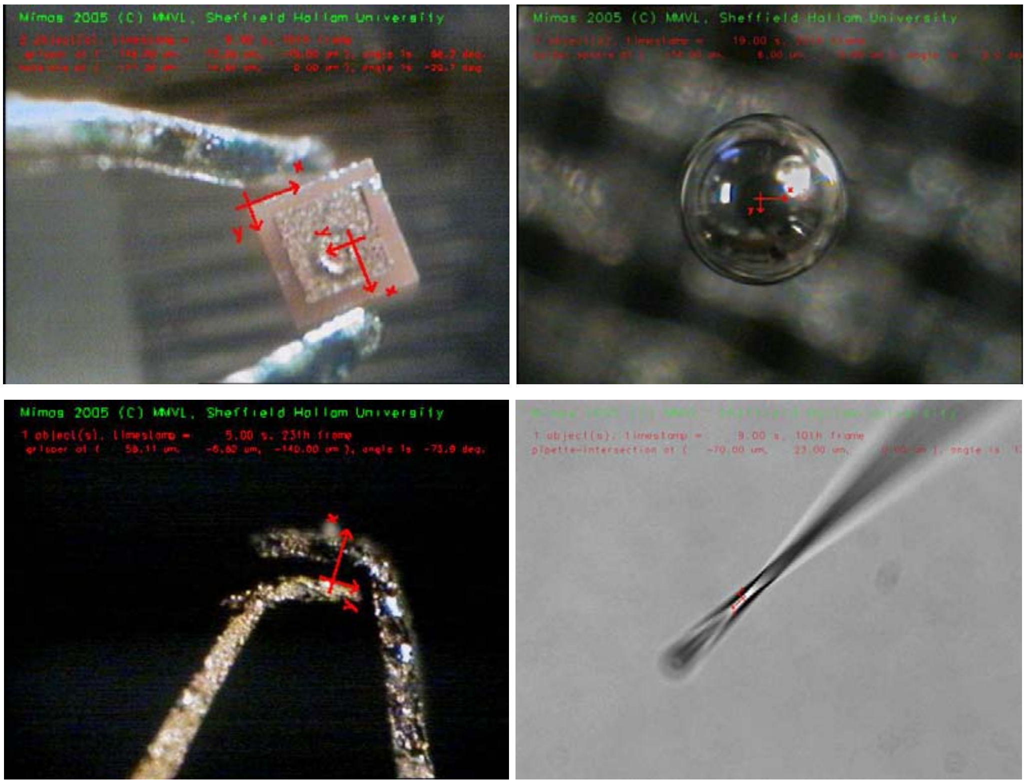
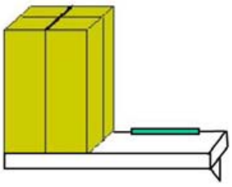


Figure 24: Some images taken with the on-board camera system: grippers manipulating a small capacitor (top-left), solder sphere on a gel-pack (top-right), steel grippers on dark background (bottom-left) and pipette tip immersed in water (bottom-right).

After analysing the benefits of some the algorithms in this class, it was decided to implement a technique called *geometric hashing*. Geometric hashing is an algorithm that uses geometric invariants to vote for feature correspondence. Geometric invariants are based on feature locations, which are invariant with respect to transformations of the object. Geometric hashing uses a voting table, which can be computed at the pre-processing stage. During recognition, there is no need to re-search over the model anymore and thus object recognition can be achieved in real-time. The algorithm allows the recognition of objects in three dimensions and with up to four degrees-of-freedom, i.e. the three translational degrees-of-freedom and the rotation around the optical axis of the camera system.

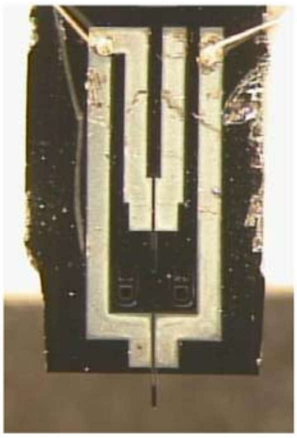
5.6 AFM-based local position sensor

The local position sensor is based on an AFM scanner mounted on a rotor high motion positioning actuator. The AFM sensor consists on one position *scanner* and one *cantilever*. The scanner is made of 4 PZT stack actuators that permits movements with 3 DOF (x,y,z) and the cantilever contains a force sensor based on a piezoresistance.

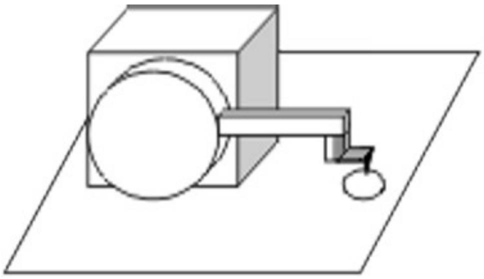
AFM scanner specifications: Dimensions: $3 \cdot 3 \cdot 5 mm^3$ Z range: 2um XYZ range: $1 \cdot 1 \cdot 1 um^3$	

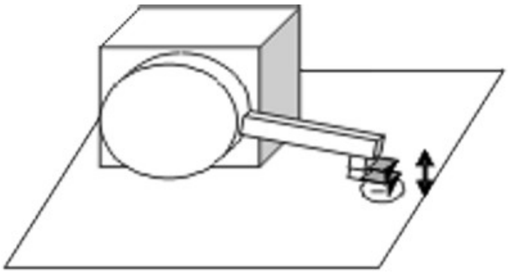
Force Constant	1 N/m*
Resonant frequency	38 kHz*
Resistance	2 k
Total Cantilever length	305 µm
Thicknes	3 µm
Tip height	>2 µm
Tip aspect ratio	2:1*
Sensitivity to displacement	1 x 10^{-6} nm^{-1}*
Sensitivity to force	0.7 x 10^{-6} nN^{-1}*

** This values can be self modified by the Park Scientific FIB*

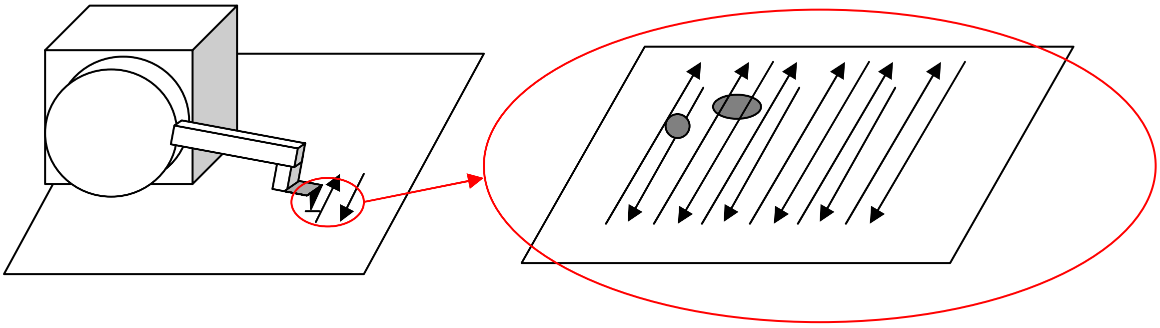


There are two different working principles:





“Z” Positioning sensor: It is used when the sample can be seen with an Inverter optical microscope. The idea is to locate the sample with the microscope and position the AFM-scanner tip over the cell. Obtain large “z” movements with the rotor and then accuracy motion with the AFM-scanner. The force sensor will give us the position of the sample related to the ground.



“XYZ” Positioning sensor: It is used when the sample is invisible for any optical microscope. The idea consists on drawing the tip through the whole area with a feedback force control system. With this mode of operation, we can extract XYZ maps and locate the sample with high resolution.

5.7 Integrated multi-robot simulation and planning system

The purpose of the implemented Autonomous Execution module is to address on-line autonomous sensor-based motion planning. The Autonomous Execution module together with the position sensing system, implement an integrated sensor based system, which drives the hardware.

5.7.1 Autonomous Execution module

The basic block of the sensor-based multi-robot control system is the Autonomous Execution module. It comprises the following blocks:

- A parser, which performs syntactic analysis to the user input task sequence
- A task supervision unit, which generates data structures with goal configurations, tool commands and control parameters. The task supervision unit also monitors and supervises the task execution process
- An autonomous motion coordinator, which is running the core navigation algorithm. The output of the coordinator is directly fed to the position sensing system.
- A World Model, which includes objects of:
    - Real robots
    - Real objects (obstacles, cells, etc)
    - Real workspace

There are three major differences between autonomous execution module and simulation module:

1) During the sensor-based autonomous execution the World Model hardware robots substitute the simulation robots. Also the drives and sensor system are activated.
2) During the sensor-based autonomous execution the velocity vector produced by the navigation algorithm is fed to the Position control, which in turn drives the hardware robots.
3) During the sensor-based autonomous execution the robots configurations are estimations of the actual robot positions and orientations. These estimations are obtained by a Kalman filter.

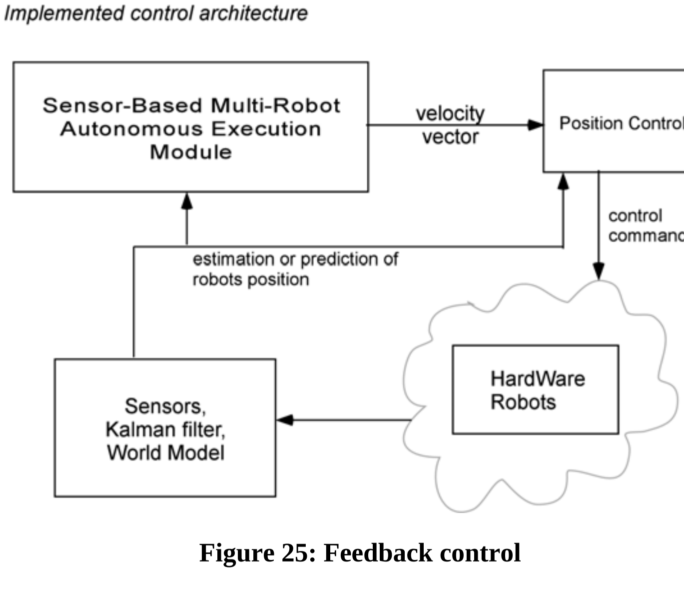


Figure 25: Feedback control

The parser, the task supervision unit and the core navigation algorithm of the sensor-based autonomous execution module are similar to those of the Simulation module. The loop of the sensor-based multi-robot control system closes at the autonomous execution module. There is also a nested loop, which closes at the position control module. The implemented position sensing system adopts a 2-stage approach:

- Creates offline an inverse actuator model using learning methodologies;

- Implements learning algorithms to enable compensation of parameter deviations during runtime. The output of this system is fed to the inverse actuator model.

The nested loop serves as a feedback in a learning process for compensating parameter deviations. It does not implement feedback control. Figure 25 illustrates the outline of the control architecture of the sensor-based multi-robot control system.

5.8 Position Control System

A robust and at the same time flexible position control is a precondition to accomplish complex tasks. In order to get the robots follow the desired trajectory several issues needs to be addressed:

- Different robots (Miniman4 as camera robot, different MiCRoN robots) have completely different movement behaviours
- The dimensions and type of the drive command differ (*e.g.* different number of DOF's)
- Parameters are not constant over time and may lead to changing conditions
- The movement is highly non-linear and tends to become chaotic at higher velocities using Piezo-driven robots.
- The AEM – depending on the operation mode – needs a reliable underlying control system; two closed loops working at the same time have to be avoided.

These reasons have motivated a two-staged approach for the position control. In this scheme, a driver that works in open loop only equilibrates non-linearities and balances the differences between different robots. At a higher level, a closed loop controller can base on a more or less linearised driver and is in charge of compensating the remaining deviation.

5.8.1 Driver

The driver is needed to transform the signal coming from the controller output into a signal that is used to drive the actuators. Obviously, the composition of this hardware signal depends on the robot type and its number of actuators.

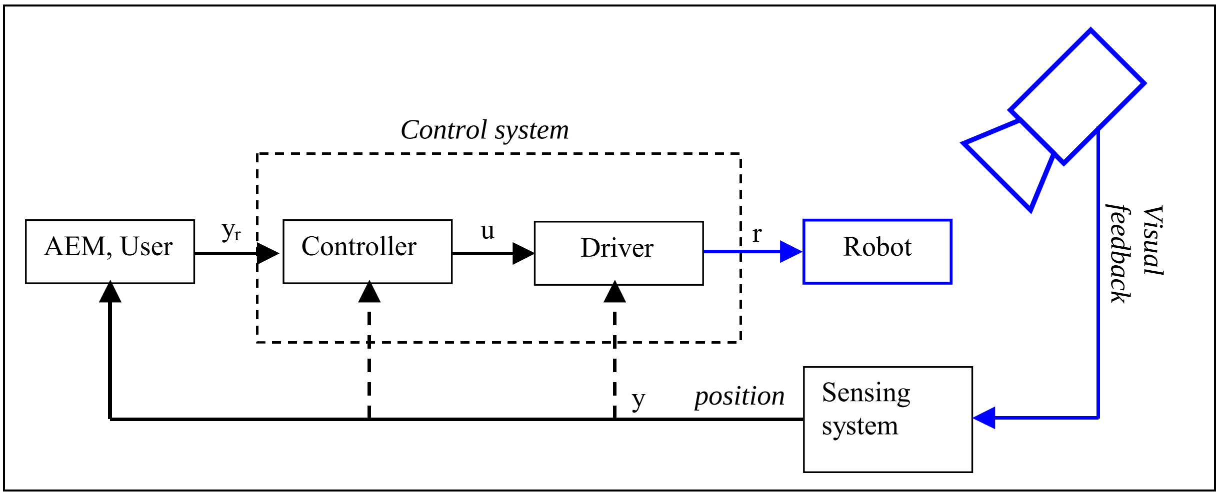


Figure 26 : Overview over the control system and its dependencies

Hence, the driver is a mathematical model of the inverse actuation. The setting of the model parameters is done offline in a calibration process. Different approaches to build the model have been tested which include not only different types of analytical models but also neural networks.

5.8.2 Simulation Modules for the Position Control

5.8.2.1 Introduction

The main purpose of the simulation unit is to verify the feasibility of the input task sequence to be autonomously and cooperatively executed by the robot agents. Simulation can detect two types of infeasible plans:

- Infeasibility that might occur due to discrepancies between the task requirements and the hardware availability;
- The infeasibility that might occur due to workspace and obstacle constraints.

If the Task sequence of the Plan is validated by the Simulation module, then a set of goal configurations and tool commands are dispatched to the Autonomous Execution module for on-line autonomous sensor based motion planning and control. The main units of the Simulation module are the Parser, the Task Supervision unit, the Motion Coordination and the World Model unit. The software architecture of the simulation module was implemented using C++ object oriented programming.

The different modules realised are:

- Simulation Module: An experiment (such as pick and place an object) is considered a Plan. Each Plan is decomposed into Tasks and each Task is decomposed into Primitive Tasks. The user, through a user-friendly input Task sequence and a set of parameters, determines the multi-robots operation
- Task Supervision Unit: This unit is responsible for:

  a. Generating data structures containing goal configurations and tool commands, which are dispatched to the core navigation algorithm,

  b. Consistency checking between task execution requirements and World Model simulation objects,

  c. Running the Navigation algorithm and monitoring the Task execution process.
- World Model Unit: The World Model (built by IPR) during on-line autonomous execution holds a set of pointers to

  a. Real objects,

  b. Real robots, drivers and sensors,

  c. Real workspace.

  The discrepancy between the World Model used in simulation stage and the World Model used in autonomous execution stage is that in the former case simulation robots substitute the real robots and the drivers and sensors are deactivated.
- Navigation algorithm: The navigation algorithm is based on the concept of Navigation Functions. Appropriate extensions have been devised so the methodology can be successfully applied to multi robot navigation scenarios. Navigation functions are real valued maps realized through cost functions, whose negated gradient field is attractive towards the goal configuration and repulsive obstacles.

5.9 First Microrobot system Prototype

5.9.1 Robot design and robot assembly

The robot design has been divided in 5 parts, each of them corresponding to a specific module and having a responsible partner:

1: Carrier; 2: Tool module; 3: On-board electronics; 4: Wireless communication; 5: Powering.

The tools themselves (micro-needles, micro-grippers, micro-syringes) have been developed separately by different partners, which include the integration into the robots. Various techniques for assembly and electrical connection between the modules have been evaluated (*e.g.* micro-flex, flip chip, wire bonding) and in some cases tested. Standard flexible PCB connected by soldering has been chosen for the final robot assembly.

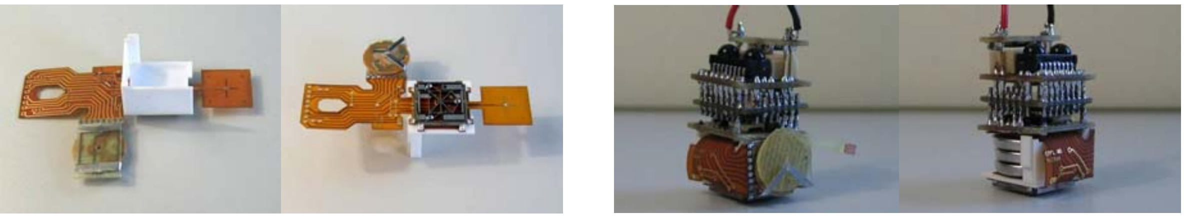


Figure 27: left: robot during assembly, the tool and locomotion modules are fixed on the flex PCB, right: final robots

5.9.2 Actuators

5.9.2.1 Rotary actuators and Micro-grippers

The actuator consists of a piezo-electric part of which two zones in the shape of the perimeter of a circle sector are liberated by some laser cuts and activated by electrode structuring (see picture below). When excited with the same electrical signal, these active zones expand, resulting in a small rotary movement of the inner part. A disk with a V groove on its perimeter is glued on top of the rotating inner part. The rotor of the actuator is provided with three cylindrical pins that slide in this V-groove. One of these pins is attached on a spring element in order to provide the required preload.

The maximum velocity is about 4 rpm with a ±200V sawtooth signal at 3 kHz, which is more than sufficient for micromanipulation applications. More important is the sub-μ resolution at the tip of the actuator. The output torque has been measured to be as high as 100 μNm.

A micro-gripper has been integrated on this rotor (figure above). It consists of one passive finger and one monomorph piezo-actuator. The gripper obtains an aperture of 126 μm when not actuated and 73μm and 267μm when actuated (i.e. ± 1.07μm/V).

Two tethered micro-robots have been equipped with micro-grippers. On one robot, the gripper (one active finger as described above) has been assembled perpendicularly to the rotational axis, while the second one (two active fingers) is parallel to it (figure below).

These two tethered robots have been used to performed micro-manipulation by adhesion experiments in tele-operation mode.

5.9.2.2 Conclusion and perspectives

Several innovative micro-actuators with submicron resolution have been developed by EPFL. These actuators have been integrated on tethered cm^3-sized micro-robots, which have been successfully used for several micromanipulation tasks.

The proposed monolithic push-pull actuators are perfectly adapted for miniaturization and low cost production. They have already been used in several prototypes of mobile robots as well as of manipulators for applications in nanotechnologies and biology.

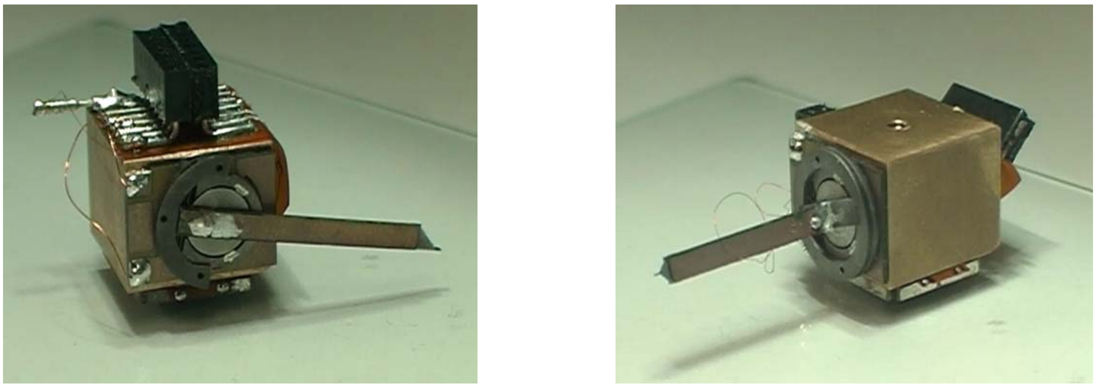


Figure 28: Micro-robots with integrated rotary actuators and grippers assemble in two different configurations.

The EPFL has now started to investigate the possibility to use these actuators as ultrasonic actuators. The preliminary results are promising. Velocities higher than 15 mm/s have been reached together with an excellent positioning resolution of a few nanometres. Their stability and controllability is also excellent. Further tests are being realised at EPFL and it is expect to publish the results in spring 2006.

5.9.3 Robot Mounted Sensing System

5.9.3.1 On-board AFM, experiments with tethered micro-robots

Figure 29 shows a scan of the pits in the polycarbonate surface of a CD-ROM realized with the AFM scanner integrated on the tethered micro robot. The total image size is about 11µm x 11µm and has been scanned with a maximum voltage of the scan stage of ±100V. The distance between the lines of pits is about 1.6µm. The line frequency for all tests was between 0.5 and 5Hz, depending on the scan size. It is difficult to control the tip deflection if the scanning velocity is increased.

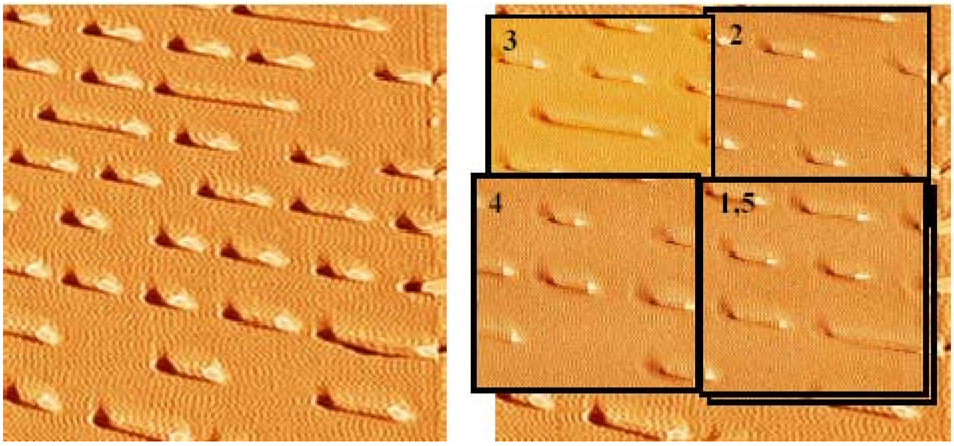


Figure 29: lycarbonate surface of a CD-ROM (line distance 1.6µm) scanned with the 2DOF AFM scanner. Image size: 11µm x 11µm. Size of the "sub-images" 1 to 5,: 5µm x 5µm.

5.9.3.2 3 DOF miniature scan stage

With the 2 DOF scanner, an external piezoelectric element is needed to bring the AFM probe to the surface of the samples and to keep it at a constant distance during scanning. EPFL has studied various 3 DOF scanner designs and two solutions have been realised and characterized.

In one solution (Figure 30 a), the Z motion is obtained by adding PZT forming a monomorph structure in the fore-arms of the scan stage.

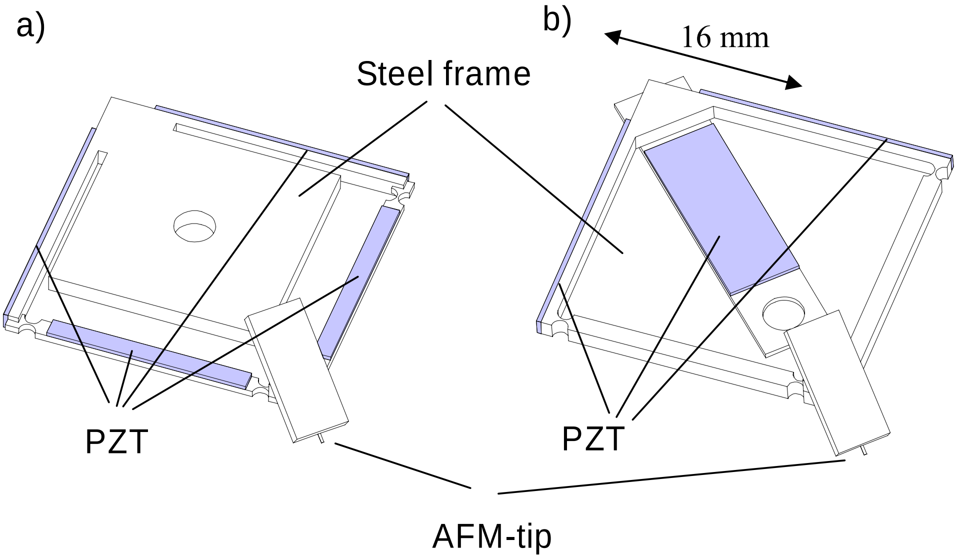


Figure 30: Scan stage designs with 3DOF with two (a) or one (b) monomorph element for the scan in Z direction.

In the second solution (b, in the figure above), the whole stage is fixed on a monomorph plate. The Z displacement is obtained by the tilting of the stage.

After optimisation, the two solutions present similar performances in terms of scanning range in the plan (typically 1.6 µm @ 30V), natural frequency in Z (typically 520 Hz) and cross talk between X and Y (typically 10%) and X-Y and Z (typically 2%). Solution b) offers a larger Z range (typically 4 µm against 2 µm). Solution b) is also easier to assemble.

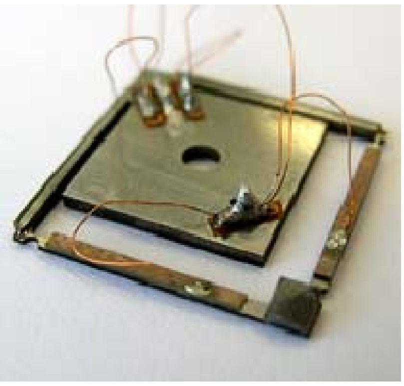


Figure 31: Scan stage solution (a). The 2 piezo- monomorphs are visible on the fore hands.

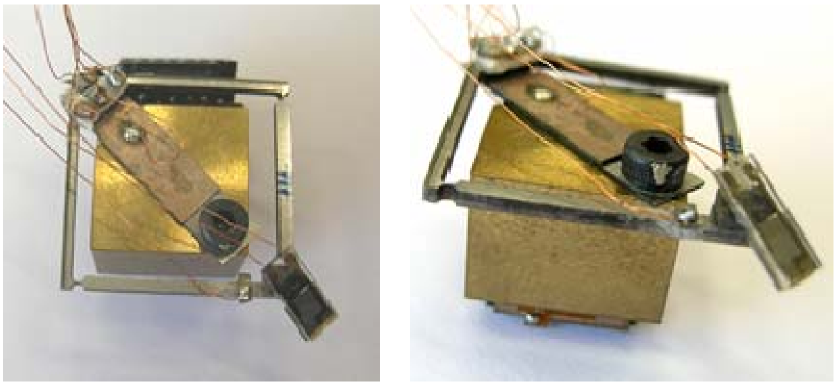


Figure 32: Scan stage solution (b) on a tethered micro-robot. The stage is equipped with the AFM probe.

5.9.3.3 AFM holder

The AFM tool (Figure 33) is based on three main components: 1) the AFM probe with the integrated piezoresistance, 2) an AFM holder for easy probe exchange and 3) the XYZ scan stage.

The silicon structure of the AFM probe is fixed on a PCB to which it is connected by wire bonding. The two contacts of the piezoresistive element on the cantilever are arranged on the top and the bottom of the AFM PCB. The AFM holder assures the mechanical and the electrical connection by a flexible elastic contact on the top and a fixed contact on the bottom of the AFM PCB. Bottom and top contact layers are laser cut. The cupper elements have been gold-coated for a good electrical contact.

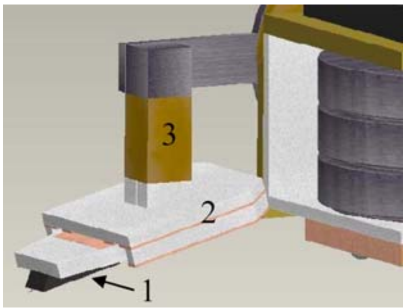


Figure 33: The AFM tool on the micro-robot: 1 AFM probe, 2 AFM holder, 3 XYZ scan stage

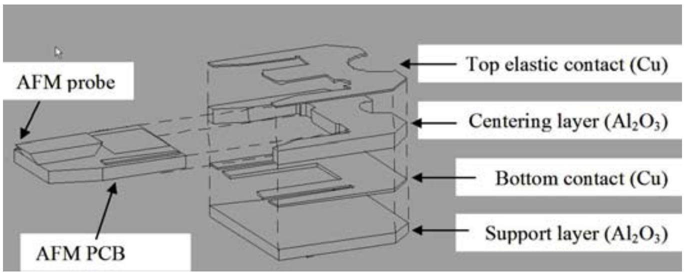


Figure 34:Exploded view of the AFM holder

5.9.4 Micro manipulation by adhesion with collaborating mobile micro robots

A simple micro manipulation platform consisting of two cm^3-sized micro robots with four degrees of freedom each has been developed to experiment micro-manipulation by adhesion. Four different strategies for grasping, transferring and releasing a micro object by adhesion have been tested. For each strategy the interacting forces have been modelled and the results compared with the real behaviour of Ø40 μm pollen spheres. Both theoretical model and experimental results show that the developed micro robots and the proposed strategies are well suited for the manipulation of the proposed micro objects. However, the simple test platform used for these experiments has shown its limits. A new test platform has been developed that makes the operator task much easier (will be realised the next months).

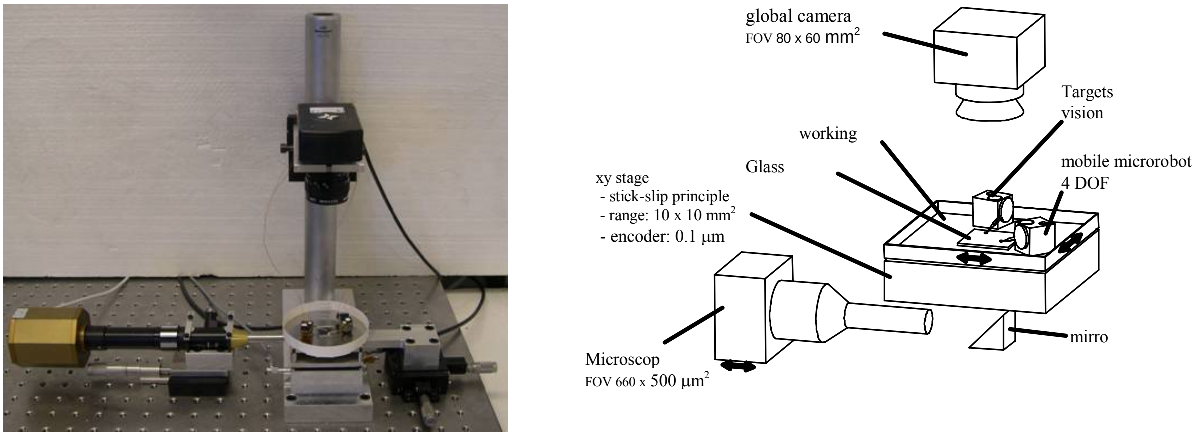


Figure 35: Left: general view of the advanced test platform for micro-handling experiments; Right: schematic view of the test platform

5.9.5 Robot design

The first robot prototype consists of several modules, each realized by a different partner:

- Actuation modules
    - locomotion module (EPFL)
    - arm actuator (DMS)
- Tool modules
    - Micro injection chip (FhG)
    - AFM scanner (UB and DMS)
    - Micro gripper (SSSA and DMS)
- Electronics
    - driving electronics (UB)
    - electronics for IR communication (FhG)
    - power pack (batteries or power coil) (FhG)
- Elements for assembly (EPFL)

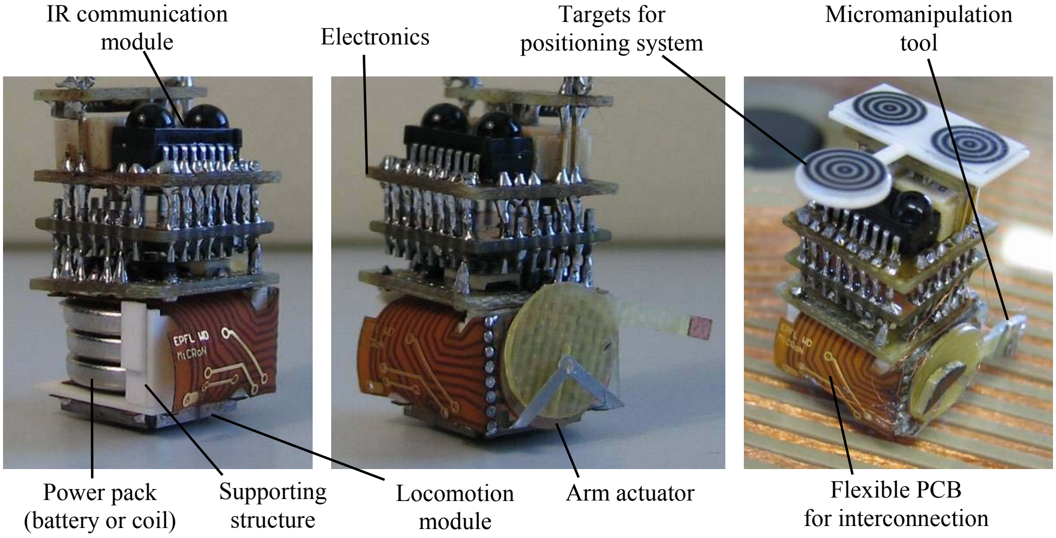
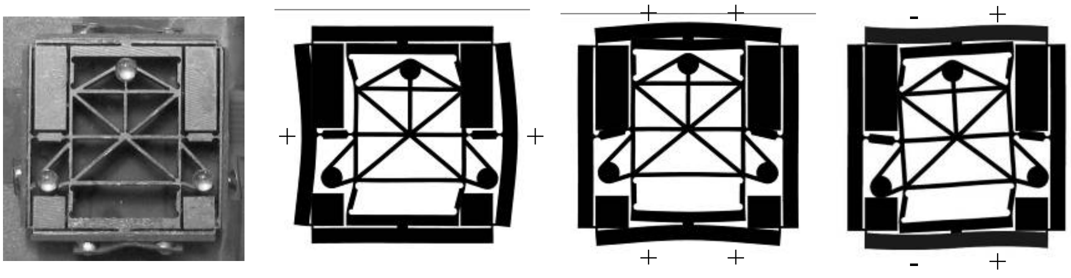


Figure 36: Different modules of the final prototype

5.9.5.1 Locomotion module

The locomotion module ($10 \times 10 \times 1\ \text{mm}^3$) consists of a titanium frame, in which a flexible structure is cut out by laser machining (Figure 37 a). Titanium has been chosen for its mechanical characteristics and its relatively low conductivity, in order to reduce the shielding effect of the magnetic filed generated by the power floor. Four piezoceramic bars are assembled to the frame on the sides and three sapphire half-spheres, serving as feet, are glued on top of the circular surfaces of the frame. The assembly of the piezo actuators on steel results in four heterogeneous bimorph actuators (also called “monomorph” or “unimorph” actuators), of which the deformation is combined into *XY*-motion of the feet by the flexible steel frame (Figure 37 b and Figure 37 c). The electrodes of two of the four bending actuators are split in the middle. A rotational displacement of the platform is thus obtained by applying an opposite voltage to both electrode halves (Figure 37 d). A long-range motion is obtained for the three degrees of freedom by applying a saw tooth signal, resulting into a stick and slip motion of the robot. Hence the locomotion platform provides the micro robot with three degrees of freedom (X, Y, θ_z) for three independent driving signals. Once the desired position is within the distance of one step length, the robot switches to the scanning mode and reaches its final position by applying a slowly varying DC voltage to the piezoelectric actuators. Repetitive steps of 7 nm forth and back have been realized with this locomotion platform. The combination of stepping mode and scanning mode within the same locomotion platform results in the unique combination of a long-range motion with a nanometric resolution.



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

Figure 37 Locomotion module ($10 \times 10 \times 1\ \text{mm}^3$) (a) based on the stick-slip principle with working principle for translation in X (b) and Y (c) direction and for rotation (d)

5.9.5.2 Arm actuator

As for the carrier, piezoceramic actuator material and a step repetition mechanism is utilized for the rotational actuator. However, a monolithic multilayer piezoceramic, fabricated with a rapid prototyping technology developed for MiCRoN was also used for the gripper. Finally, a quasi-static walking mechanism was chosen instead of a stick-slip mechanism. For miniaturized systems, i.e. low moving mass, the quasi-static motion mechanism potentially has better accuracy and in addition the peak currents are lower.

Three identical bimorphs are arranged in the tangential direction of a circle requiring only 2 drive signals. Together with the monolithic approach this fulfils the aims (D1-03, D1-05) of having simple driving and assembly. The rotational actuator, the stator, is mounted on a printed circuit board and an arbitrary tool can be integrated directly onto the rotor that is held in place by a steel spring, see Figure 38. The rotational actuator can generate a pure rotation and a pseudo translation of different tools.

Voltages as low as 7 V can be used for driving, but for reliable performance the 20 V available is hardly enough, rather the initially planned (D1-03, D1-05) 48 V are required. The maximum torque of the motor is 80 µN at a drive voltage of 50 V and a spring force of 1.2 N.

The rotational actuator has extremely good motion resolution (0.1 μrad) for frequencies up to about 80 Hz (0.1 rpm). Fast transport can be achieved in the frequency range 3-6 kHz (4 rpm). The power consumption for these frequencies is about 1 mW and 80 mW respectively.

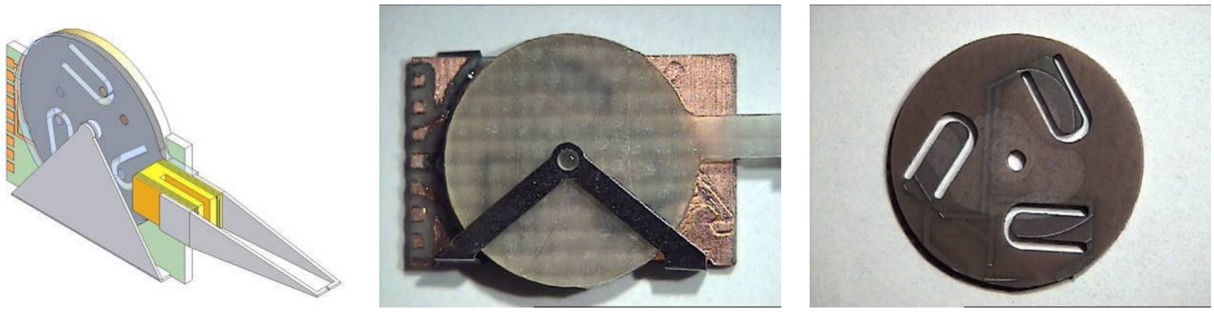


Figure 38 Micromanipulation module with rotational actuator (∅ 9.2 mm) mounted on printed circuit board with tool (gripper) integrated directly onto the rotor (left). Micromanipulation module without tool (middle). Rotational actuator (right).

5.9.5.3 Micro-Injection Chip

The microfluidic SyringeChip integrates monolithically a micro needle, a thermo pneumatic micro pump connected to this needle, and a sensor. The dimensions of the chip are 2.2 × 2.2 × 1 mm^3. The micro needle as well as the area around the micro needle is made of translucent materials (silicon dioxide, glass). Filling of the chip is done by simply dipping the needle into the fluid to be injected.

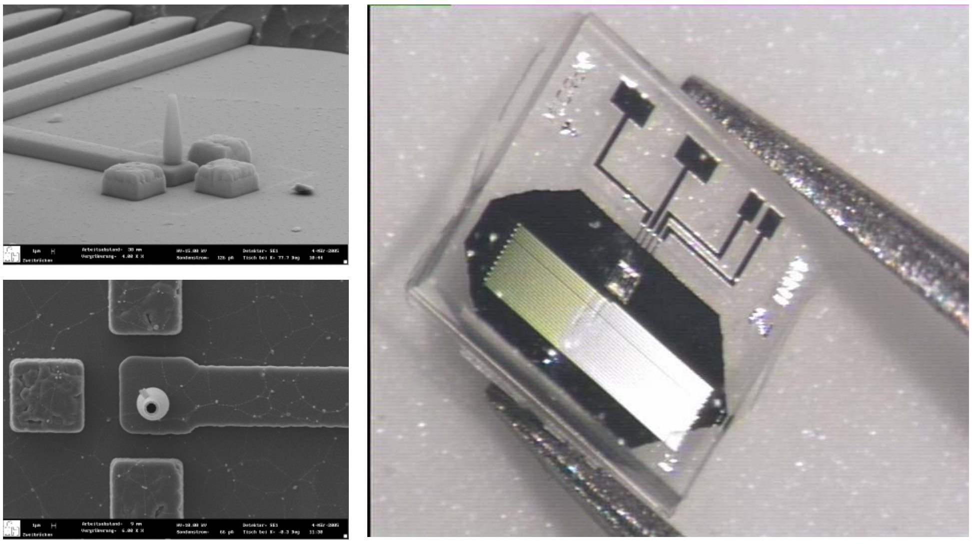


Figure 39 SyringeChip with close ups of the micro-needle with tip diameter 2 µm, needle length 25 µm.

In contrast to commercially available injection systems the size of connecting tube and pump of the IBMT chip is adapted to the volume to be injected. Once filled, the chip can be used to perform several hundreds of injections. The injection volume can be adjusted and controlled very precisely. Power consumption of the SyringeChip is less than 2 mW for up to 2 pl injection liquid and the integrated actuator can be controlled by a PID-controller or even a Pulse-Width-Modulated signal. The realized micro-needle has an outer tip diameter of 2 μm and a length of 25 μm (see Figure 39).

A special SyringeChip holder has been developed by DMS in order to be able to exchange a broken syringe chip with a new one, without having to resolder any electrical contacts. The syringe chip holder consists of a small PCB with some tracks that is screwed on the arm of the robot. In order to screw and unscrew this syringe chip holder without exercising any force on the arm actuator and the body robot, a supporting block has been fabricated at EPFL in which the end of the arm can be fixed by means of a clamping mechanism.

5.9.5.4 AFM scanner

The designed and implemented AFM tool consists in two parts: sensor and actuator. The sensor is a piezo-resistive AFM commercial probe, which is connected to the actuator by means of a special holder developed by EPFL. The actuator is a multilayer piezoceramic element, which can be moved in three orthogonal directions.

The actuator consists of four piezoelectric stacks (dimensions: $2 \times 2 \times 3, 5\ mm^3$) allowing the position control of the AFM tip with a resolution in the range of nanometres. The piezo-actuator acts as bimorphs but the partition into four independent elements, makes them three-axial, moving in X and Y directions (for making scanning experiments) and in Z direction (for making nanoindentation experiences).

The holder ensures the electrical and mechanical connection between the piezo-actuator and the AFM sensor. This holder is suited to the space requirements and, in addition, it establishes a mechanical connection with the sensor without the need of resoldering, allowing an easy interchange of various AFM tips.

A cantilever is the main part of this classical AFM sensor with a sharp tip probe at its end and the laser force detection system. In our case we only use a self-sensing cantilever which has silicon piezo-resistance deposited over it.

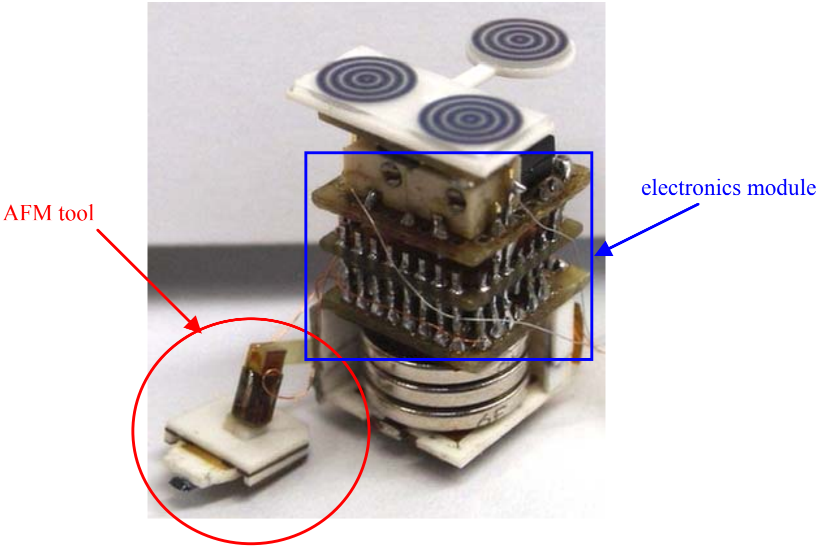


Figure 40 The microrobot equipped with the AFM tool.

When the cantilever bends, the resistance value depends linearly on the strain of the piezo-element (this is true only for low variations). With this system, a dramatic reduction in terms of size and power consumption compared to classical AFMs is obtained. The self-sensing probe used as a sensor is a Veeco PLCT-VPMT piezo-lever AFM tip. It has an integrated piezo-resistance that varies its value related to the sensor displacement. The most important technical characteristics of the tips are 1N/m of force constant, 38 kHz of resonance frequency, nominal resistance of 2kΩ±20% and resistance sensibility of $0.7nN^{-1}$

5.9.5.5 Micro gripper

This micro gripper design consists of a U-shape piezoelectric actuator which has steel micro gripper arms glued to its tips. The U-shape actuator is a monolithic structure consisting of two multilayer unimorph actuators. The passive part of each unimorph actuator consists of passive piezoceramic material, while the active part consists of 11 layers of piezoelectric material separated by ground and phase electrodes. Although in this work, U-shaped actuators were used for the steel grippers, in theory separated bar shaped actuators could also be used.

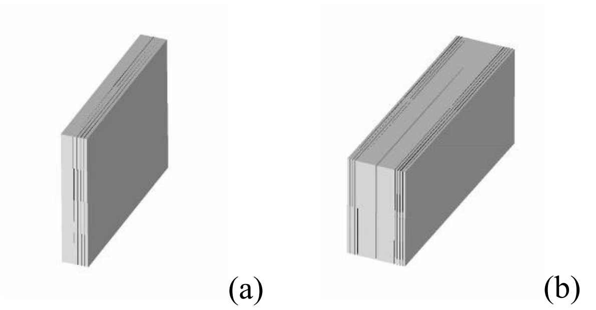

(a) (b)

Figure 41 Drawing of bar–shaped (a) and U-shaped (b) piezoactuator. Mean dimensions are: 2.35 x 1.65x0.3 mm^3 for (a) 3.6x1.5x0.85 mm^3, with 2.9 mm long parallel structures for (b).

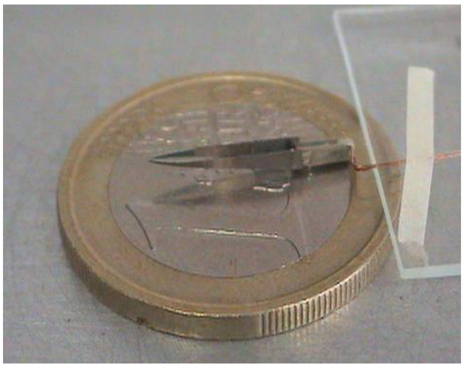


Figure 42 Steel micro gripper with piezo-electric actuator (total length ±13 mm)

The stainless steel gripper tips were machined using wire EDM. Wire EDM is normally used for machining 2D shaped, and to manufacture a 3D gripper arm required that the 2D profile of the gripper was first cut out of a mounted piece of stock stainless steel. To realize the 3rd dimension, this cut piece was then mounted at 90 degrees to the first cutting plane, and then the piece was cut from above. The minimum tip thickness was about 70 μm, which is a limitation imposed by the wire EDM machine.

Once these stainless steel gripper arms were cut out, they were glued to the piezoelectric actuator. The glue was used sparingly to ensure that this glue did not spread over the sides of the actuator, causing a restriction to the bending. To align the gripper tips, one needs to use slow curing glue so that the gap distance of the tips can be adjusted if necessary. The realized gripper features a displacement of 20 μm for a voltage of 20V for each gripper tip, so a total span of 40 μm.

5.9.5.6 Driving electronics

The main challenge of the microrobot implementation is the size minimization with powering and communication autonomy. The electronic module is designed to perform the following predefined robot capabilities: communicating with the host PC; driving 10 piezoelectric actuators; sensing and controlling the nanotool.

In order to accomplish these requirements, 4 different modules are designed and implemented: Power source generation module (PSG), Input sensing for control system (ISC), Mixed signal IC module (MXS) and Power addressing and amplification IC module (PAA). All these modules are full custom designed and placed on 4 printed circuit boards of 12mmx12mm.

The integrated circuits' PCB integrates a full custom mixed-signal IC (the robot "brain"), two full custom power amplifiers ICs (for drive the piezoelectric actuators) and the system clock. The ICs are soldered by the use of the flip-chip technique and the interconnections are done by wire-bonding. The MXS IC is the responsible of interfacing with the IR protocol, generating the appropriate signals (trapezoidal, saw tooth and triangular) for motion of the microrobot and closed loop control of the tool by an externally programmable digital PID. The signals coming from the MXS module are amplified in the PAA module in order to drive the actuators.

5.9.5.7 Electronics for IR communication

The communication system between individual robots and the host was developed as a single-master multi-slave topology. Robots act as slaves to the host (master). Inter-robot communication is neither implemented nor required. The host issues commands to single robots and waits for a response, *e.g.* AFM measurement data or an acknowledge indicating that the command has been understood.

The IR processing unit is implemented in the MXS chip of the electronics. It receives the infrared transmissions from the host computer and decodes the information within. If requested, data transmissions are acknowledged or tool data is acquired and sent back to the host. A flexible design allows three different types of Vishay Semiconductors' IR transceivers to be connected: TFDU8108, TFDU6108, and TFDU6102.

The infrared communication implies that every data packet is received by all robots of the cluster. To address only one single robot, unique identification numbers (ID) are (dynamically) assigned to the robots. Data packets containing an ID are interpreted by the corresponding robot only. In addition, broadcasting is possible to control all robots at once, e.g. for stopping the robots simultaneously.

5.9.5.8 Powering module

In the solution of wireless power transfer, the power pack gets power through a miniaturized robot coil from an alternative magnetic field that is generated by an external magnetic field generator, the so-called Power Floor, which provides a travelling magnetic field throughout the working area of about 200 × 200 mm^2. The robots power pack can therefore receive a constant power in the whole area. The operating frequency is defined as 500 kHz.

The coil power pack with resonant, rectifying and filtering circuit is designed in a volume of 11.5 × 11.5 × 4 mm^3. In order to reduce the skin effect, the coil is wound with 200 turns of Litz-wire, which is composed of 30 twisted ϕ0.03 mm enamel copper wires.

The output voltage depends directly on the intensity of the external magnetic field, which is tuned to transfer a power output of 330 mW / 3.3 V from the coil power pack.

The coil power pack is sensitive to metal parts around it because the eddy current generated in the metal parts changes the magnetic field around them significantly. Experiments showed that, e.g., a copper plate that has the same diameter as the robot coil could reduce the transferred power by 90% when it is put just under the coil. Therefore, large conductive parts near the coil should be avoided.

5.9.6 Power consumption of the robot

In order to reduce the power consumption the different amplifiers of the driving electronics can be switched on and off in certain groups. Hence, different operating modes have been defined:

- STANDBY: idle mode, only communication possible
- CARRIER4: for locomotion module when 4 signals are necessary.
- CARRIER3: for locomotion module when 3 signals are necessary.
- AFMSCANNING: for AFM tool operating in scanning mode, 4 signals are necessary.
- AFMNANOIDENDATION: for AFM tool operating in nanoindentation mode, 4 signals are necessary.
- ROTOR: for arm actuator, 2 signals are necessary.

The power consumption of the second (ROBOT2) and the third (ROBOT3) prototype assembled can been seen in Table 4 for a supply voltage of 1,8V. The rather large difference in power consumption between the different prototypes is believed to be due to small short circuits and parasitic capacitances in the onboard electronics. The power consumption ROBOT2 is the lowest of all three prototypes and this robot has been successfully supplied by the power floor.

	ROBOT2		**ROBOT3**	
	Current [mA]	**Power [mW]**	**Current [mA]**	**Power [mW]**
Stand by	55	115.5	79	142.2
Carrier4	165	346.5	260	468
Carrier3	141	296.1	249	448.2
Rotor	60	126	135	243
AFM	174	365.4	216	388.8

Table 4: Measured power consumption and supply current at a supply voltage of 1.8Vfor the second (syringe) and the third (gripper) robot assembled

The powering experiments with ROBOT2 also showed that there is no interference between power floor and IR communication and between power floor on the onboard electronics, as bidirectional communication was possible in the SIR and the MIR mode while the robot was being powered by the power floor.

5.10 Test-bed for the untethered robot system

5.10.1 Integration of the control system

The evaluation system has been set up. It provides a platform to integrate the whole MiCRoN system including powering, communication, controlling, vision and so on. A two-staged approach has been developed for the position control system. It consists of a driver that operates in open loop and a controller that is in charge of planning and closed-loop control, the Autonomous Execution Module. The controller uses the feedback of the vision system. The driver is based on a mathematical model that represents the inverse actuation of the robot. The model is calibrated offline. Different learning techniques have been tested, including genetic programming.

To get the robots follow a desired trajectory, several challenges needs to be addressed:

- Different robots (Miniman4 as camera robot, different MiCRoN robots) have completely different movement behaviours
- The dimensions and type of the drive command differ (*e.g.* different number of DOF’s)
- Parameters are not constant over time and may lead to changing conditions
- The movement is highly non-linear and tends to become chaotic at higher velocities using Piezo-driven robots.
- The AEM – depending on the operation mode – needs a reliable underlying control system; two closed loops working at the same time have to be avoided.

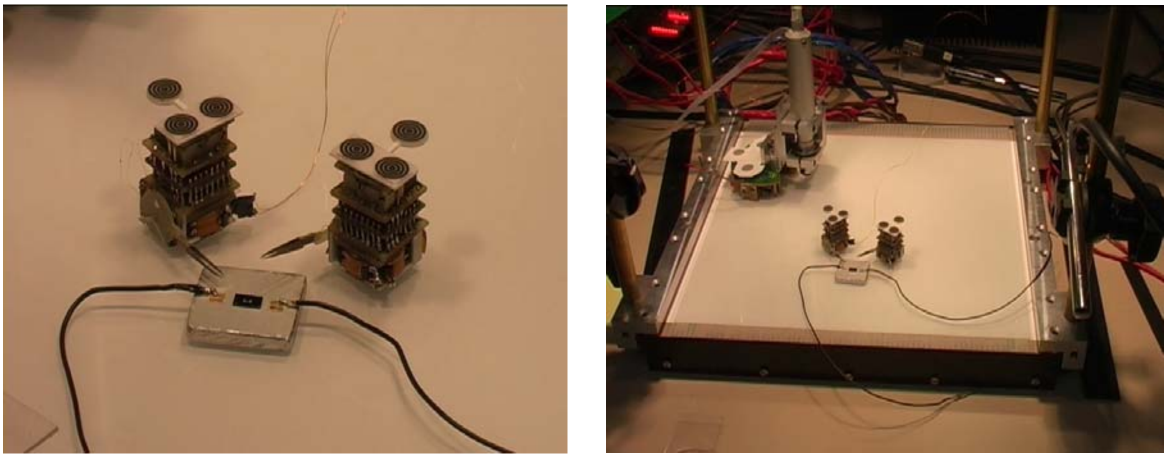


Figure 43: The test bed fort he untethered robots

These reasons have motivated the two-staged approach mentioned above. In this scheme, a driver that works in open loop only equilibrates non-linearities and balances the differences between different robots. At a higher level, a closed loop controller can base on a more or less linearised driver and is in charge of compensating the remaining deviation.

5.10.2 User Interfaces

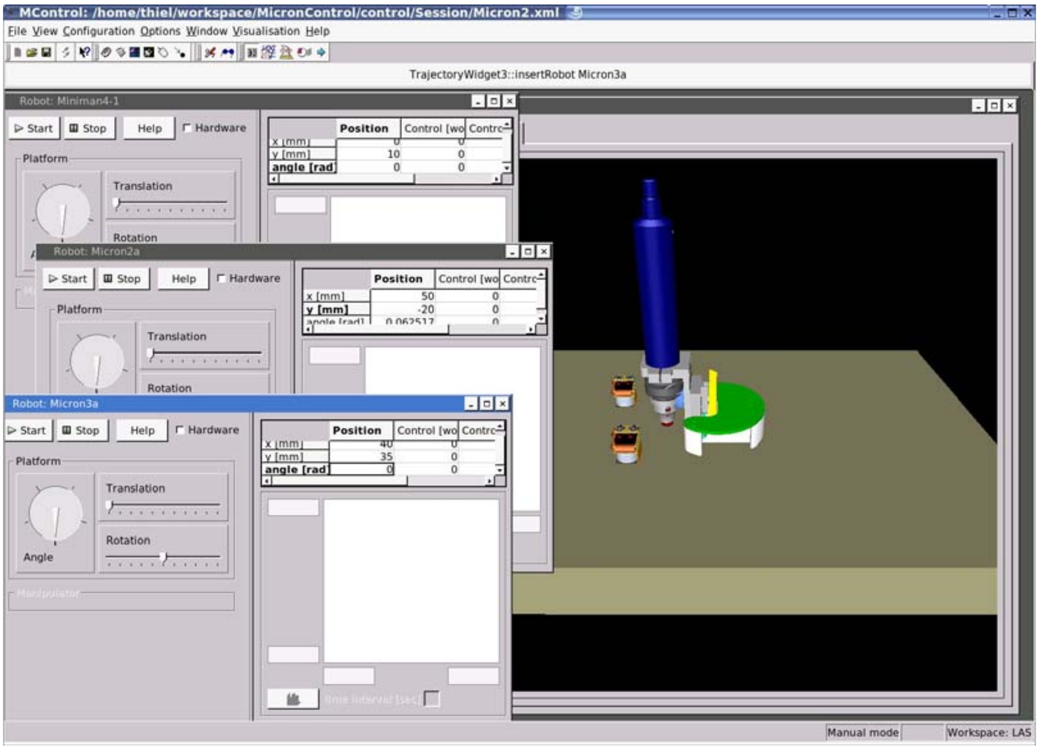
Main purpose of the user interface is to enable the user to interact with the controlled system. The definition of tasks and the setting of parameters can be done in an easy, user-friendly way and the results of the current process are shown both in textual and graphical manner.

There are two different ways to set-up a specific configuration. Either by loading an already defined session from a file or by integrating all required elements stepwise into the selected workspace the user can configure his system. There is a set of typical test scenarios already available in files (XML-format); new ones can be created very easily.

For each robot object created, there will appear a command window, which enables the control and supervision of the robots movement. The control output and position data for each D.O.F. are displayed in both textual and graphical way. Additionally, there is an overview window in 3D that indicates the current position and orientation of each robot as well as the pose of each micro object detected.

There are five different operation modes for the robots that can be selected individually:

- A task mode that allows the online definition of a set of tasks (movement commands) for a specific robot.
- In the direct mode the user can move the robot by a simple graphical selection of speed (percentage of the maximum speed of the corresponding robot) and direction.
- The planning mode gives access to the Autonomous Execution Module, which enables the user to perform complex tasks with various robots and collision avoidance.
- By selecting the space mouse mode the user can take advantage of the very easy and intuitive way to drive the robot using the space mouse.
- A target mode to drive the robot to a specific position.
- An online documentation can be accessed by the 'help' menu. Some helpful documents concerning the GUI usage and also a complete description of the implemented C++ classes can be accessed here.



Robot: Miniman4-1

	Position	Control [wo	Contrc
x [mm]	0	0	
y [mm]	10	0	
angle [rad]	0	0	

Robot: Micron2a

	Position	Control [wo	Contrc
x [mm]	50	0	
y [mm]	-20	0	
angle [rad]	0.062517	0	

Robot: Micron3a

	Position	Control [wo	Contrc
x [mm]	40	0	
y [mm]	35	0	
angle [rad]	0	0	

Figure 44: Screenshot of a scenario with 2 MiCRoN and the Miniman4 camera robot

5.10.3 Network

For a variety of reasons, one computer is not sufficient to control the whole system. In fact three or even four machines are required:

- The main server where the control, visualisation and sensor tasks are running.
- Another machine for sending the reset signals. The reset-by-IR strategy requires a high sample rate and absolute priority over other process. So it needs to have its own processor.
- The global positioning system (task 4.1) runs on Windows, so another computer is required.
- The object recognition software (task 4.3) requires high computational power. It is not really a must, but at the end it came out to be better to run it at another machine.

The different computers are connected by an Ethernet TCP-IP connection on a separate local network. Figure 45 shows the basic configuration.

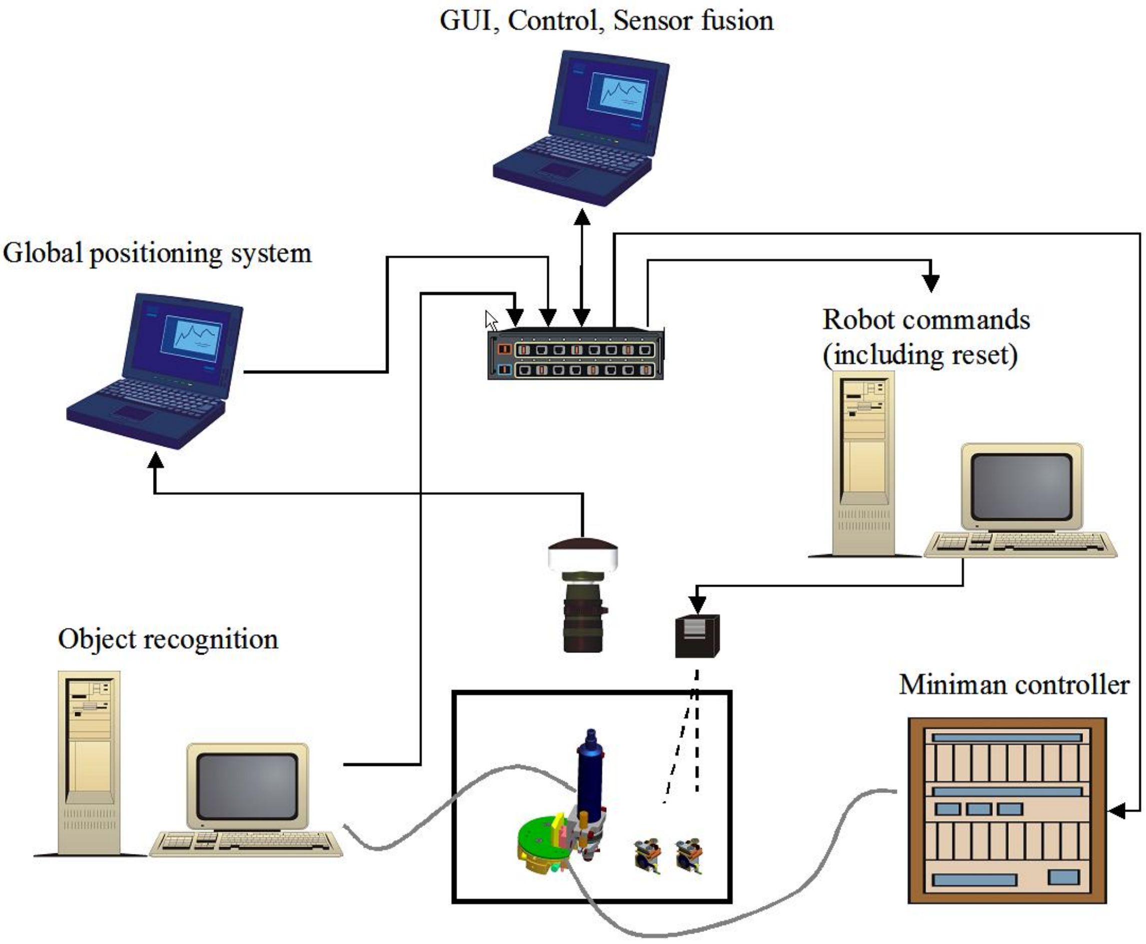


Figure 45: Hardware configuration

5.11 The Different Experiments

5.11.1 3D-Assembly Demonstrator

One of the main tasks was to design and test a 3D assembly experiment which would demonstrate the ability of the MICRON robots to work together to complete an assembly task. It was decided in the final analysis to design a micro-soldering whereby two robots could cooperate at a micro-workstation to solder a micro-component to a small PCB. In the macro-work, several ways exist to bond components, such as:

- Soldering iron with liquid/ solder wire flux
- SMT with screen printing of solder paste

On the micro-level, designing a kind of micro-soldering iron introduces a large amount of technical challenges such as design and manufacture of equipment, heat transfer problems due to laws of scaling, and power consumption, to name but a few. It was for these many reasons that this concept was rejected. Screen printed likewise was obviously rejected. A suitable concept was therefore desired whereby the heating necessary to bond the component with the PCB did not come from a tool mounted on the micro-robot, but was supplied by a workstation independent of the robot. In this plan a basic progress concept was designed as:

1. Robot places micro-PCB on micro-hotplate
2. Robot placed 30 µm solder spheres on contact pads of PCB

3. Robot then takes component and places on PCB
4. Hotplate activated and cooled, melting solder and connecting component to PCB
5. Robot removes finished circuit from hotplate

It is important to note that all testing of the SSSA 3D assembly task was performed by a 3 axis micromanipulation station (DC motor, 1µm accuracy) and that all trials were performed in this way. The attachment of gripper to the robot and final execution of the process was to be performed only once all of the 3D assembly process was thoroughly tested by using the traditional 3 axis manipulation station.

Giving the following critical components of the process:

1. Micro-hotplate (to be now called *micro-hotplate workstation*)
2. *Solder spheres*
3. Suitable *micro-component* to be soldered to the PCB
4. Suitable small PCB or demo circuit on which the micro-component will be soldered (to be now called *micro-circuit*)
5. Micro-tools necessary to handle and place various components of the process (*micro gripper*)

The next step was to locate these necessary components of the process. The micro-hotplate for the micro-hotplate workstation was found in the form of a gas sensing system which has been developed by the University of Neuchatel, Switzerland, and represented an already developed heating plate capable of reaching a maximum temperature of approximately 500 degrees Celsius in less than one second. This represented an ideal platform on which the PCB could be placed for heating. The images below show the micro soldering workstation with two SSSA grippers in view, and on the right a close-up of the hotplate heating element (platinum).

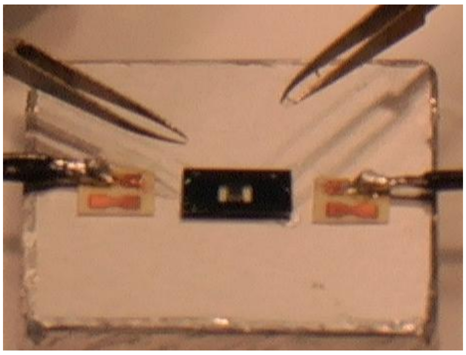


Figure 46: Micro soldering workstation with two SSSA grippers in view

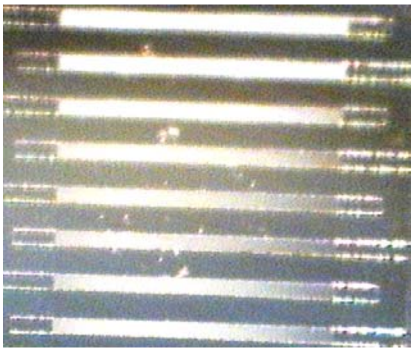


Figure 47: a close-up of the hotplate heating element (platinum)

The solder spheres were taken by filtering out the component solder particles of a commercially available solder paste using acetone in several filtering steps, giving the necessary solder spheres in large quantities. Average size of the spheres is 30µm. The image below shows the gripper grasping one of these solders spheres.

Figure 48: SSSA gripper grasping a solder sphere

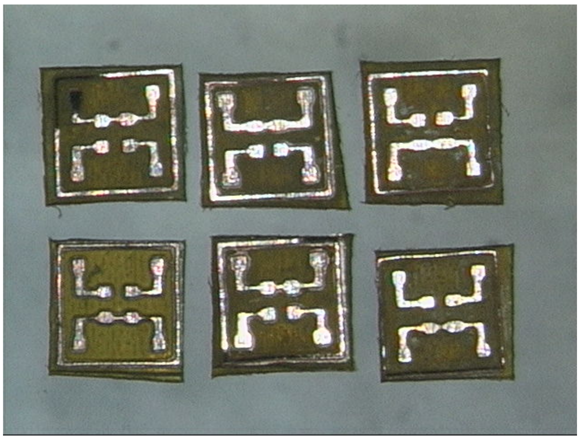


Figure 49: Test soldering circuits

The micro-component was finally chosen as an SMT resistor of size 150 x 300 µm, developed and supplied by Taiyo Yuden, to our knowledge the smallest SMT component available in the world at time of receipt. Other components were tested such as a square capacitor of size 175 x 175 µm. Both these components are shown below.

Regarding the development of a microcircuit, it was decided to manufacture a circuit which would allow several components to be soldered, and also to allow wire bonds to be made. In the end a simple circuit of size 1.5 x 1.5 mm square was made using Kapton and standard photolithography. Much smaller circuits could be made, however for the basic demo this size was deemed sufficient.

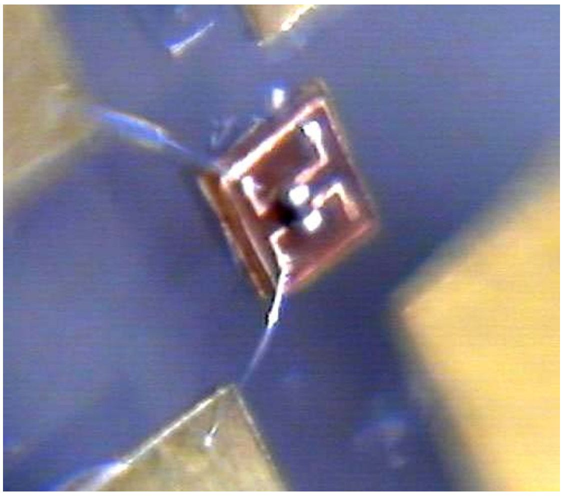


Figure 50: Bonding Example

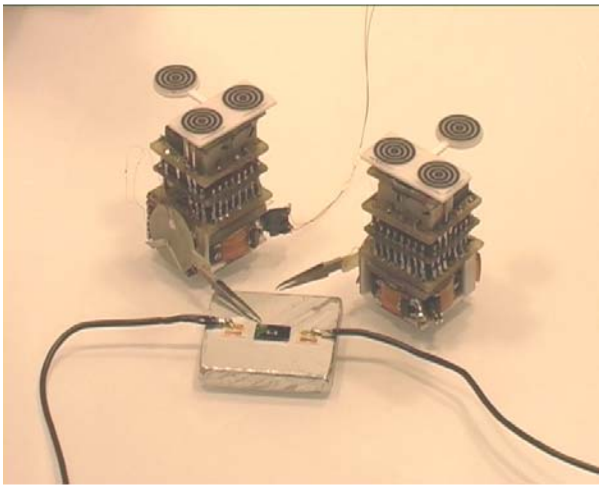


Figure 51: Final experiment (SSSA)

5.11.2 Biological and biomedical Nano manipulation demonstrator

The SyringeChip and the electronics are attached to one micro-robot of the MiCRoN robot-cluster, which is controlled by a host PC-system using infrared communications. An inverse microscope, on which the whole set-up can be mounted (see Figure 52), is used for observing the manipulation process.

The micro-robot with the SyringeChip must perform a liquid-loading-step before the experiment starts. The liquid to be injected (diacetyl-fluorescein) is able to prove the penetration of the cell-membrane and the survival of the cell. The cell integrates the injected liquid into its metabolism and starts to fluoresce under ultra-violet lighting. The injection-liquid is prepared in a separate Petri dish close to the SyringeChip micro-robot. Controlled by the host-system and the on-board electronics, this micro-robot navigates to the injection liquid reservoir. By lowering the robot's arm, the SyringeChip's needle tip is immersed into the liquid. Having resided in that position for about 10 seconds, the SyringeChip has been loaded, as the liquid is pulled into the channel system due to the capillary forces. The micro-robot raises its arm to remove the needle tip from the liquid. Henceforth, the robot is ready for microinjection.

In the centre of the work area, a Petri dish containing suspension cells (human acute myeloid leukaemia HL-60, 15 µm diameters) is placed above the microscope's objective. A standard glass capillary dips into the culture medium positioned within the view port of the microscope. It is connected to a commercial micro-injector with manual pressure control. Controlled by the host system via infrared communication, the micro-robot equipped with a cell-moving tool pushes one cell close to the micro-injector's capillary. If several cells were taken at once, the cell selection process has to be retried until only one single cell has been caught and fixed by adjusting the pressure with the micro-injector. When a cell has been attached, the micro-robot A withdraws from the cell, clearing the area for other robots. Then, the micro-robot C with the microfluidic SyringeChip is remotely guided close to the fixed cell.

To prevent the cell from slipping away, it is important that the angle between the injection needle of the SyringeChip and the cell-fixing glass capillary is close to 180°, so that the cell membrane can be penetrated perpendicularly to its surface. Next, the host controller sends the injection command to the micro-robots electronic system, which in turn controls the micro-robots actuators pushing the SyringeChip's needle tip through the cell membrane. When penetration has been achieved, the on-board electronic system activates the PID-controller to increase the air temperature inside the SyringeChip's actuator by 0.2 °C. As a result, a liquid amount of 0.2 pl is injected into the HL-60 cell. Considering the PID-parameters, the host-system must wait for about 4 seconds before the command to retract the injection needle is sent. After switching on the ultra-violet-light source of the inverted microscope, the manipulated cell can be observed. If it is fluorescent after a certain time, typically 1-2 minutes, it is assumed that the liquid has been injected into the cytoplasm and that the cell is still alive, because it has integrated the injected fluid into its metabolism.

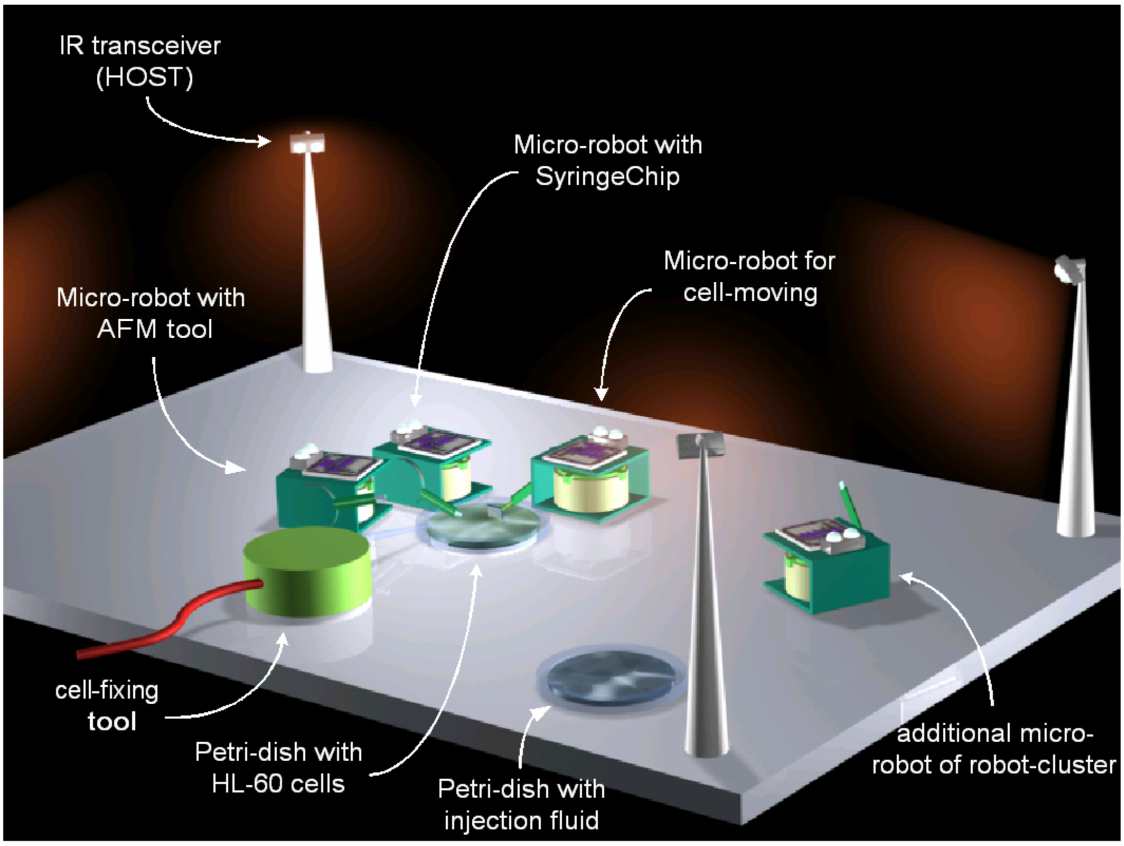


Figure 52: Set-up for the MiCRoN robots.

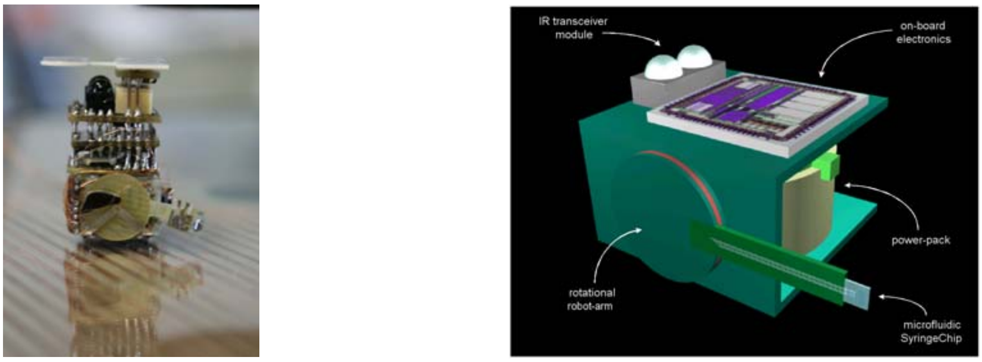


Figure 53: Single MiCRoN robot with integrated SyringeChip (real robot and 3-D-Simulation).

6 Potential Impact of Project Results

6.1 Rotatorial Actuator

The rotating motor used in the manipulator arm developed for the MiCRoN project has been designed with the specifications for several important motor applications in mind. The combination of forces in the gram range, a speed well above 1 cm/s and operation in the ultrasonic range is desired in many products, e.g. consumer electronics and toys. The small size makes it possible to integrate the motor where there is an extremely limited space and the mass-production technology makes it possible to compete also where the cost is of main importance. The commercialization of the technology has been initiated and some particular application areas are being analysed. The potential impact of the motor technology is difficult to estimate but most of the motor applications considered correspond to volumes in the multi million range with prices in the Euro range. Since there is a multitude of similar applications the total potential could be considered great.

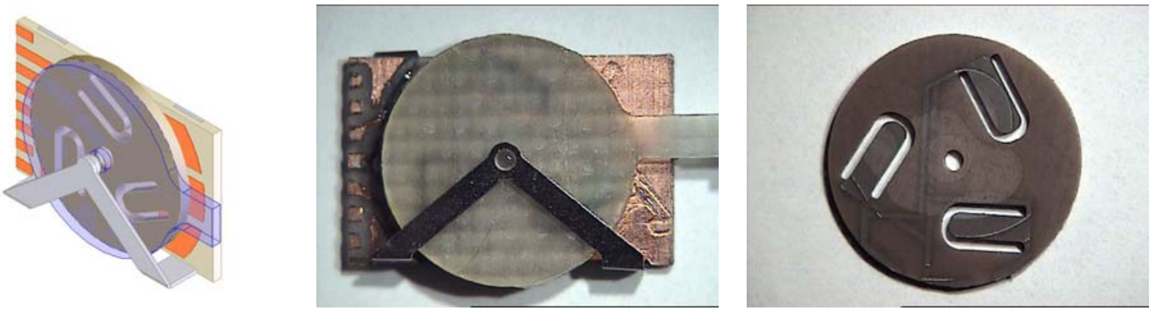


Figure 54: Rotational actuator (∅ 9.2 mm) mounted on printed circuit board. Rotational actuator (right).

6.2 Robot Platform Technologies

The results obtained at EPFL thanks to MiCRoN project will be exploited as follow:

1) Several companies have shown their interest in the monolithic push-pull piezoactuators (MPA). Two German companies are particularly interested; however, the technology is not yet mature to be directly exploited. EPFL applied for a patent (PCT/CH04/00099 “Monolithic piezoelectric actuator”).
2) These developments are currently pursue in the FET project « I-SWARM: Intelligent small world autonomous robots for micro-manipulation », FP6-2002-IST-1, 507006. These developments aim to go further in terms of miniaturisation, mass-production and very low power consumption.
3) The obtained results will further be developed at EPFL in the frame of other research projects. Three EU projects in the last call of FP6 (IST and NMP) have been submitted. If they are funded, the monolithic push-pull actuators principle will be exploited and improved for various applications in biology and nanotechnologies.
4) The test platform described in task 7.1 will be used for student works at EPFL. It is an excellent test bench for various research activities in the domain of micro-robotics.

6.3 Syringe Chip and IR-Communication

During the course of the project two patents have been filed by partner Fraunhofer-IBMT (FhG). One patent regards the power floor and a second patent the developed syringe chip.

The German company Eppendorf has been contacted during the BIOTECHNICA exhibition in October 2005. This company is a manufacturer and supplier of injection needles and other equipment used for performing cell injections. Eppendorf has shown great interest in the syringe chip.

During the next year it is planned to try to find companies (e.g. Eppendorf) who are willing to start a contractual research project with FhG. It is the goal to exploit the expertise gained during the course of the MICRON project for the development of new cell injection equipment. The filed patent as well as the positive results of the MICRON project presents a good starting point for negotiations with companies. But the patent does not only concentrate on cell injections. It also protects other dispensing tasks like dispensing of glue which can be performed with the developed syringe chip. Thus a broad range of applications and companies are available for future exploitation efforts. Additionally the technologies which have been optimised for the fabrication of micro needles can be used for similar but larger needles which can be used for other applications. Since a few years research activities are going on which aim at the development of arrays of micro needles for transcutaneous drug delivery. The MICRON results can be used as a basis for new research projects on micro needles for drug delivery.

It is also planned to exploit the developed power floor. Up to now no company has been found who is interested in the power floor or at least in the new concept for inductive power transfer. During the next year partner FhG will intensify these efforts.

6.4 Simulation and Task Planning

The main research results by NTUA during the micron project can be summarized to the following:

- Extension of the Navigation Functions Methodology to the field of multi-robot navigation
- Development of a methodology for automated planning of motion tasks for multi-robot systems
- Extension of the non-smooth back-stepping methodology to systems with bounded velocities
- Development of a new class of discontinuous navigation functions suitable for navigation in dynamic environments
- Development of motion models and corresponding control laws for micro robot navigation.
- Extension of navigation functions for navigation in uncertain environments

Moreover the proposed methodologies introduce novelties

- In the way of computing multi-robot navigation functions: This new way does not only contain the robot to robot distances but also the distances from all possible collision configurations
- In automated planning of motion controllers: The motion controllers can be composed based on Linear Temporal Logic specifications to create a motion task
- In automated planning of motion tasks: Motion tasks are composed as modules based on the job description in the state space to create a hybrid system that carries out the task

- In handling uncertain environments: The notion of belt zones is introduced around the non-modelled obstacles and an appropriate vector field is installed in the zone capable of driving the robot to a region from where the convergence procedure can be resumed
- In navigating micro-robotic systems: A new kinematic model is created that allows actuation of the system in region of low actuation error. A discontinuous controller is applied to project the navigation vector field to the new kinematic model.

The main field of application of the proposed methodologies is the micro-robotic systems. The proposed motion models and their corresponding controllers enlarge effectively the application field of the proposed methodologies to autonomous wheeled and air vehicles. The proposed methodologies can be applied to agriculture, to the production industry, in military applications, in space exploration, in the entertainment industry and other applications.

6.5 Vision and Image Processing Technologies

The research activities carried out by SHU during the course of the MiCRoN project have led to the design and implementation of hardware/software solutions in the area of microscope imaging and machine vision. Generally speaking, vision algorithms that work well in the macro-domain are not always portable to the microscope domain, where typical effects such as limited depth of field and image noise make these algorithms unstable and not robust to a number of external conditions, such as lighting. The solution proposed in this project combines two robust algorithms for recognition and tracking in a framework that allows for robustness to noise, ease of use and re-usability in other similar application domains where 2½-D object recognition and tracking using a single camera view is desirable.

In the MiCRoN project, a compact microscope unit integrated on a mobile robotic platform has been designed and realised. Although this imaging device cannot replace large and powerful optical microscopes used today in a large variety of application domains, it represents an alternative and cheap solution that can be effectively utilised in many applications where physical constraints in the work area and the requirement for a mobile platform make the use of this small unit preferable to a traditional optical microscope.

In the near future, we intend to further develop our camera prototype using more recent miniaturised optical and imaging components as well as including new components such as an integrated LED light source for autonomous operation. At the same time, we will be continuing the development of the vision software to address current limitations as well as to make it portable to a variety of applications.

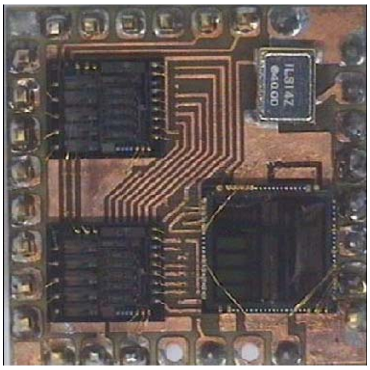
The successful integration of these technologies and the realisation of such a flexible and portable imaging system will open up the way to possible commercial exploitation, especially if industrial partners with a strong interest in this research sector can be found. We are currently focussing in this direction and are confident that we will soon be able to attract industrial collaboration into this project.

6.6 AFM-Scanner and Electronics

6.6.1 Full custom integrated electronics for low-voltage low-range AFM scanners

Electronics have been divided in two main blocks, namely a controller and high voltage drivers. The controller is a partially configurable Integrated Circuit which main function is communication via an IR link with a central system and the generation of different type of waveforms for control of mobile parts. The drivers provide enough power to drive specific piezoactuators. With both ICs the system is able to generate most of the types of signals required for micro positioning based on piezoactuators.

Concretely the controller IC is able to:



- Perform communications with a central base through an InfraRed Controller incorporated on-chip. This capability together with a battery operation allows eliminating the cable link to communicate with typical positioners and hence, allows to access places for measurements which are not accessible by conventional equipments.
- Generate triangular, sawtooth and trapezoidal waveforms for piezoactuator control with programmable amplitude, waveform discretization (up to 512 samples per period) and frequency. The waveform generator covers practically all the required situations for positioning. It is possible to stop waveform generation and perform a step-by step accurate positioning.
- Compensate for mobile parts mismatch and drivers offset. The controller has programmable gain and offset to compensate to first order possible mismatches in the connected components (piezoactuators in the MiCRoN application). The suppression of offsets in the driving amplifiers sets optimal conditions for actuation (maximum dynamic range and precision).
- Closed-loop operation with an incorporated a PID control for accurate positioning and control of actuation. All the incorporated Analogue to Digital and Digital to Analogue Converters have a resolution of 10b. So nanometric precision is possible. Data measured can be sent to a central base by reading internal registers and sending data through the IR link.
- Low power consumption. The special architecture of the fabricated Integrated Circuit (GALS architecture) allows for optimal control of power depending on the operation mode. This characteristic is especially applicable when the system is battery operated.

For the analogue high voltage drivers the drivers have been designed to look for a good power consumption compared with commercial SMD operational amplifiers for the values of the piezoelectric loads, assuring enough current for the worst case of slew-rate. The compensation has been designed for a fixed gain decreasing the level of dissipation. The driver IC has a suitable logic core to define the right communications with the control core, a power-up system that generates and acknowledge signal to start the communications with the control core and avoid spurious voltage and voltage problems at the outputs, and a suitable circuitry of power down for each operational amplifier in order to have a low power dissipation in the standby mode.

6.6.2 Imaging and nanomanipulation of living microbial cells by a microrobot-AFM system

Atomic force microscopes (AFM) have been employed in plenty of nanohandling applications, including work in the fields of nanotechnologies and bioengineering. Good examples are the measurement of the electric properties of cells for nanobiosensor characterization, or the dip-pen nanolithography (DPN) for nanostructuring. The usual AFM equipments are fixed and use a single AFM probe for measurements or manipulations. Additionally the incapacity of the AFM to be used for a real-time vision control proves to be a limitation.

For most of the biohandling processes, cells have to be cultured. Usually the proliferation progress can only be controlled by removing the cell material from its culture environment. It would be a great advantage, if the cells and their proliferation could be modified (e.g. drug injection) and studied in their suitable culture environment, without removing them.

The planed activity of the University of Barcelona in this field will be based on the development of a new frame of AFM applications. The main objective is to work with living cells in a controlled and sterilized environment, for specific manipulations in the range of microscale to nanoscale, by means of a full custom designed station. Herein a new kind of application is introduced, using cooperative work between an AFM microscope and a high precision piezoelectronically driven positioning robot in a micro-reactor for cell proliferation.

For the cooperative task of nanocharacterization between AFM and microrobot a closed-loop AFM is crucial. It will have to ensure small area scanning in patterned areas several times after different chemical depositions/manipulations ensured by the microrobot equipped with a specific AFM tip. A closed-loop AFM will be able to ensure this scanning operation with a very good reliability and accuracy.

Another important characteristic will be the possibility to adapt the hardware and software of the AFM. For the cooperative task, hardware and software interfaces will be included. The AFM that may fulfil the requirement of the proposal is e.g. Nanotec AFM. This microscope is part of UB’s equipment and it will be used within the nanocharacterization robot station.

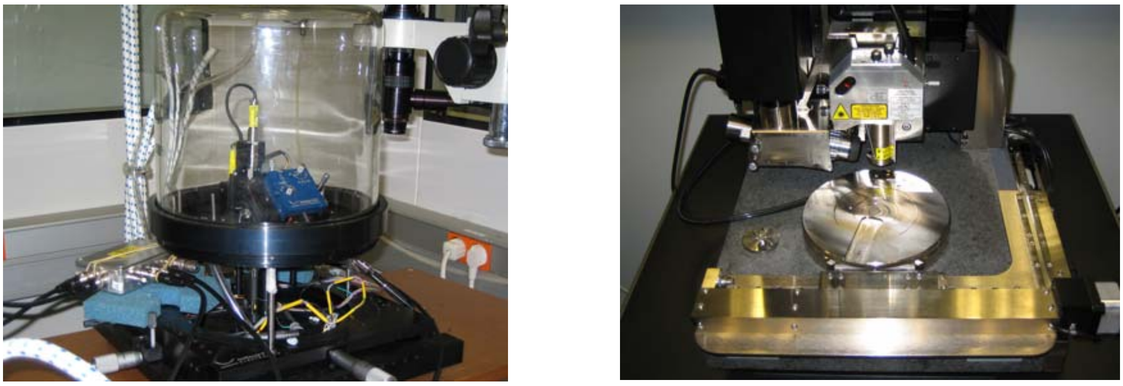


Figure 55: Photograph of two AFM microscopes (Nanotec and Dimension) available in the UB group to work in cooperation with microrobots for Imaging and nanomanipulation of living microbial cells.

6.7 New 2D and 3D Position Sensing System

The localisation system is not strictly limited to micro-robots but can be used in a variety of tasks where high precision measurements are required. Several contacts to the industry had been initialised. Currently, there are two applications on its way:

- Measuring of linearity of high precise movement axis for milling machines
- Research project proposed at the DFG regarding 3D-Moiré measurement working within the resolution of the given 2D measurement system (see Figure 56). This is one major goal to put this idea into the 3D. The decision on this proposal is expected in spring 2006.

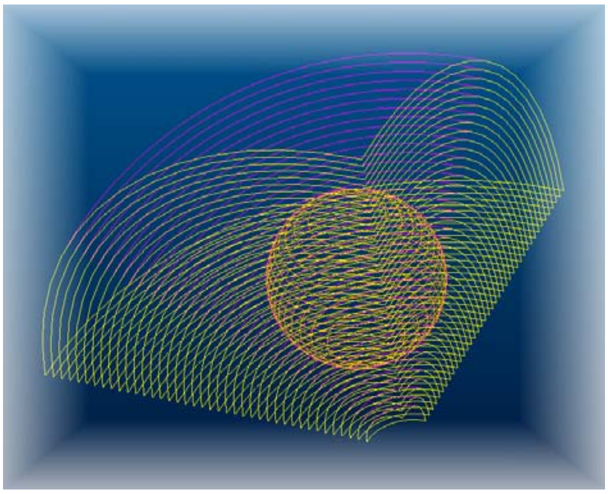


Figure 56: The 3D-Moiréeffect, as it is postulated. The idea is based upon the 2D-position sensing system realised within the MiCRoN project

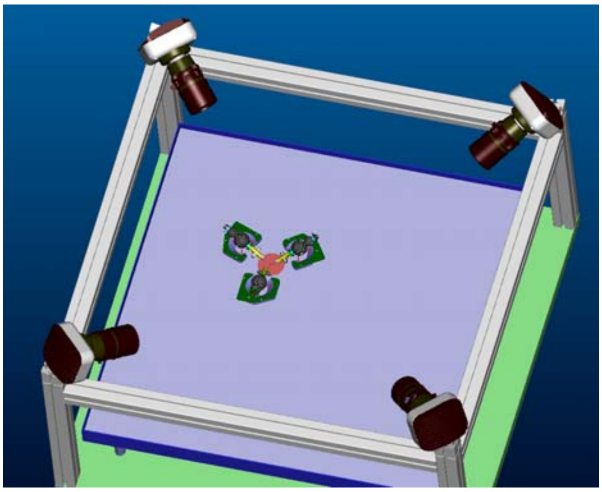


Figure 57: Basic test setup for the 3D-position sensing system

6.8 New Gripper Technologies

The development of the micro gripper that is able to handle parts down to a size of 20µm has a large impact in the micro technology community. These tools cannot only be used for autonomous and mobile micro robots because it is easy to drive and to assemble. Almost for all manipulation tasks in the micro world, this gripper can be used for object handling. The gripper designed and manufactured by SSSA in the MiCRoN project is a tool for micromanipulation of micro-objects which has the following advantages when compared to other gripper:

- Low power consumption due to piezo-electric actuator
- Low voltage requirement (25V to obtain 30 micron tip displacement)
- Small size and low weight of gripper (12mm in length)
- Fine tip geometry (60 micron tip width, EDM machined)
- Robust gripper arms (stainless steel)

This kind of gripper can be a solution when weight and power consumption needs to be concerned, as it is in the case of the MiCRoN robots. These grippers have been successfully used in the course of the MiCRoN project to perform delicate manipulations of micro-components.

Another advantage of the gripper is the power of the actuator to actuate at high force/speed. Piezo-electric actuators are well known for their high force/size ratio, and this advantage became obvious in several operations performed by the gripper. For example, in order to release objects stuck to the gripper, step voltage jumps were applied to the actuator to accelerate the gripper tip - thus if the tip acceleration is high enough, due to the inertia of the micro-component the objects were released. This was particularly useful for releasing 30 micron solder spheres, which were prone to sticking to the tips of the gripper.

Figure 58: The micro gripper

One disadvantage of the gripper developed was the small amount of gripper tip displacement per unit voltage. It was found that to manipulate a wider variety of components, a high tip displacement per unit voltage is required, giving the gripper the flexibility for further tasks. This could be solved by some further redesign and optimisation of the piezo-electric actuator. However, for the MiCRoN tasks themselves, this performance was more than satisfactory. If the actuator could be improved in future work by increasing the length of the bimorph or some other parameter, this would greatly increase the practicality and flexibility of the tool.

7 Future Outlook

The future outlook on the results of the MiCRoN project can be divided into two parts: state of the micro mechatronic components and outlook on the MiCRoN system.

7.1 State of MiCRoN components

The exhaustive lists of micro mechatronic components developed within the MiCRoN project given above can be seen as a direct starting point for future development steps. For all subsystems, research prototypes have been successfully developed. Some of the prototypes can already be considered as pre-production models.

All MiCRoN partners have stated their respective plans for the results generated during the project in the Technology Implementation Plan (TIP) and will search for future exploitation of their research results. For some of the promising results, patents have been applied for and first industrial partners have been contacted for the commercial exploitation of these results. All consortium partners are open for further collaboration on their sub-systems, and also offer consulting to third parties on their respective field of expertise broadened by the MiCRoN project.

7.2 State of MiCRoN system

As regards the integration of all subsystem into a functional micro robot cluster, a lack of time for further system integration prevented the full realization of the proposed scenarios. For this reason, MiCRoN partners have agreed to strive for further joint publications, but also to apply for additional funding by means of research exchange or mobility programmes to ensure that also the research efforts, which have been put into the project, will continue. This has proven to be effective already for the MINIMAN results, where project partners have travelled to other partners' institutions to perform additional micro handling experiments with the existing hardware.

The main idea behind the project, the development of an intelligent micro robot cluster to solve tasks that cannot be solved with a single robot, will be continued and even intensified in the context of the I-SWARM project.

In terms of commercialization potential of a micro robotic system like the MiCRoN system, the same boundary conditions as for the MINIMAN project apply: such a micro robotic system can be considered as a laboratory tool, given further system development and refinement of the man-machine interface (both in terms of software and of the robotic hardware). Companies will be contacted that have the respective market share, and given the right R&D conditions, even the complete MiCRoN system could potentially be transferred into a product via a series of system prototypes and pre-production models.

8 Disseminations

In the following an overview is given over the most interesting disseminations of all partners they had during the project.

8.1 Disseminations by DMS

8.1.1 Conference proceedings:

N. Snis, U. Simu and S. Johansson, Piezoelectric drive platform for cm^3.sized autonomous robot, Conference proceedings Actuator 2004, pp. 106-109, Bremen Germany, 14-16 June, 2004

8.1.2 Journal Papers:

N. Snis, U. Simu and S. Johansson, A piezoelectric disc-shaped motor using a quasi-static walking mechanism, Journal of Micromechanics and Microengineering 15, pp. 2230-2234, 2005

8.2 Disseminations by EPFL

8.2.1 Journal

W. Driesen, T. Varidel, S. Régnier, J-M Breguet “Micro manipulation by adhesion with two collaborating mobile micro robots”, SPECIAL ISSUE: International Workshop of Microfactories 2004, Journal of Micromechanics and Microengineering, J. Micromech. Microeng. 15 (2005) S259-S267.

8.2.2 Conference Proceedings:

W. Driesen, T. Varidel, A. Bergander and J.-M. Breguet, “Energy Consumption of Piezoelectric Actuators for Inertial Drives”, IEEE MHS, pp 51-58, Nagoya, October 19-22, 2003

W. Driesen, A. Bergander, T. Varidel and J.-M. Breguet, “Monolithic Piezoelectric Push-pull Actuators for Inertial Drives”, IEEE MHS, pp 309-316, Nagoya, October 19-22, 2003 (best paper award)

A. Bergander and J.-M. Breguet: “Performance Improvements for Stick-Slip Positioners”, IEEE MHS, pp 59-66, Nagoya, October 19-22, 2003

A. Bergander, W. Driesen, T. Varidel, J-M. Breguet: “Development of Miniature Manipulators for Applications in Biology and Nanotechnologies”, proceeding of Workshop “Microrobotics for Biomanipulation”, pp. 11-35, IROS 2003, October 27-31, 2003, Las Vegas, USA

T. Varidel, W. Driesen, A. Bergander, J.-M. Breguet, « High precision miniature rotary micro-actuator », ACTUATOR 2004, pp. 517-520, 14-16 June 2004, Bremen, Germany.

A. Bergander, W. Driesen, T. Varidel, J.-M. Breguet, « Monolithic piezoelectric actuators for miniature robotic systems », ACTUATOR 2004, 14-16 June 2004, Bremen, Germany.

W. Driesen, T. Varidel, S. Régnier, J-M Breguet, « Micro manipulation by adhesion with two collaborating mobile micro robots », IWMF 2004, 15-17 October, Vol. 1, pp. 188-193, Shanghai, China.

A. Bergander, W. Driesen, T. Varidel, M. Meizoso, J.-M. Breguet, « Mobile cm3-microrobots with tools for nanoscale imaging and micromanipulation », MECHROB 2004, Special session Micromanipulation, September 13-15, Part III, pp. 1041-1047, Aachen, Germany.

J. Brufau, M. Puig-Vidal, J. López-Sánchez, J. Samitier, W. Driesen, J.-M. Breguet, N. Snis, U. Simu, S. Johansson, J. Gao, « MICRON: Small Autonomous Robot for Cell Manipulation Applications », ICRA 2005, Barcelona, April 18-22, 2005, Spain.

W. Driesen, T. Varidel, S. Mazerolle, A. Bergander, J.-M. Breguet, « Flexible micromanipulation platform based on tethered cm3-sized mobile micro robots », IEEE International Conference on Robotics and Biomimetics, ROBIO 2005, June 29 - July 3, 2005, Hong Kong (Best Student Paper Award).

8.3 Disseminations by FhG

8.3.1 Filed patents:

A German patent on the Powerfloor has been filed.

Title:	“Vorrichtung und Verfahren zur induktiven Energieübertragung” (Translation: “Device and Method for inductive energy transfer”)
Number:	103473DE; Priority date: 8. June 2004

8.3.2 Papers submitted to a conference:

TAGLIARENI, F., VELTEN, T.: "Micro fabrication of Microfluidic Syringe Chip with Integrated Actuator". Oral presentation at Mechatronics & Robotics, Aachen, Germany (Nordrhein-Westfalen), Sept. 13-15, 2004. Proceedings (2004), pp. 173-177

J. Brufau, M. Puig-Vidal, , J. López-Sánchez, J. Samitier, N. Snis, U. Simu, S. Johansson, W. Driesen, J.-M. Breguet, J. Gao, T. Velten, J. Seyfried, R. Estaña and H. Woern: „MICRON: Small Autonomous Robot for Cell Manipulation Applications“. Proceedings of 2005 IEEE International Conference on Robotics and Automation. April 18-22, 2005, Barcelona, Spain

TAGLIARENI, F.; NIERLICH, M.; STEINMETZ, O.; VELTEN, T.; BRUFAU, J.; LOPEZ-SANCHEZ, J.; PUIG-VIDAL, M.; SAMITIER, J.: Manipulating biological cells with a micro-robot cluster. Proc. of the Int. IEEE Conference on Intelligent Robots and Systems (IROS). Edmonton, Alberta, Canada, Aug. 2-6, 2005, pp. 426-431.

RAIMON CASANOVA, ANGEL DIEGUEZ, JUANJO LACORT, ANNA ARBAT, **NIERLICH, M., STEINMETZ, O**.: „A Monolithic Control Circuit for a 1cm3 Microrobot for Biological Experiments”. Asian Solid-State Circuits Conference, IEEE A-SSCC, 2005

LACORT, J.; CASANOVA, R.; BRUFAU, J.; ARBAT, A.; DIEGUEZ, A.; NIERLICH, M., STEINMETZ, O.: „An integrated Controller for a Flexible and Wireless Atomic Force Microscopy”. Proc. SPIE 2005 - Microtechnologies for the New Millennium 2005

CASANOVA, R., LACORT, DIEGEUEZ, J., ARBAT, A., PUIG,M., SAMITIER, J., NIERLICH, M., STEINMETZ, O., SCHOLZ, O.: „A Specific Integrated Controller for Nanomicroscopy and Cellular Manipulation”. Oral presentation at Annual Conference of the IEEE International Society of Circuits and Sensors (ISCAS), Kobe (Japan), 23.-26.05.2005

JIANBO GAO: “Inductive Power Transmission for Untethered Micro-Robots”, The 31st Annual Conference of the IEEE Industrial Electronics Society, Sheraton Capital Center, Raleigh, North Carolina, USA, November 6 – 10, 2005, accepted as oral presentation

8.3.3 Papers submitted to a journal:

Jianbo Gao: “Traveling Magnetic Field for Homogeneous Wireless Power Transmission”, IEEE Transactions on Power Delivery, accepted 3.1.2006

8.4 Disseminations by NTUA

8.4.1 IEEE conference papers were produced:

S.G. Loizou and K.J. Kyriakopoulos: "Automatic Synthesis of Multi-Agent Motion Tasks Based on LTL Specifications", 43rd IEEE Conference on Decision and Control, 2004

S.G. Loizou and K.J. Kyriakopoulos: "Motion Planning of Piezoelectrically Driven Micro-Robots via Navigation Functions", 13th IEEE Mediterranean Conference on Control and Automation 2005

S.G. Loizou and K.J. Kyriakopoulos: "Automated Planning of Motion Tasks for Multi-Robot Systems," (to appear), 44th IEEE Conference on Decision and Control 2005

8.4.2 Journal papers were accepted for publication:

D.V. Dimarogonas, S.G. Loizou, K.J. Kyriakopoulos and M.M. Zavlanos: "A Feedback Stabilization and Collision Avoidance Scheme for Multiple Independent Non-point Agents", (accepted, 2005), Automatica

S.G. Loizou and K.J. Kyriakopoulos: "A feedback Based Multiagent Navigation Framework" (accepted, 2005), International Journal of Systems Science

One journal paper was submitted (under review):

S.G. Loizou and K.J. Kyriakopoulos: “Multi-Robot Navigation Functions”, (submitted, 2005), IEEE Transactions on Robotics

One conference paper was submitted (under review):

P. Vartholomeos, S.G. Loizou, M. Thiel, K.J. Kyriakopoulos and E. Papadopoulos: “Control of the Multi Agent Micro-Robotic Platform MiCRoN,” Conference on Control and Applications, IEEE, Munich, Germany, October 2006.

8.5 Disseminations by SHU

8.5.1 Internet publicity (6 June 2005)

The Microsystems and Machine Vision Laboratory (MMVL) at Sheffield Hallam University and its participation to the MiCRoN project is featured in an online article by the Yorkshire Forward Knowledge-RICH Portal (www.knowledge-rich.com).

8.5.2 Paper publications

J. Wedekind. Focus set based reconstruction of micro-objects. In IEEE International Conference in Mechatronics & Robotics (MechRob04). Aachen, Germany, September 13-15, 2004.

M. Boissenin, J. Wedekind, A.N. Selvan, B.P. Amavasai F. Caparrelli, J.R. Travis. Computer vision methods for optical microscopes. Submitted to Computers in Industry, Elsevier Science Journal (Special Issue on Machine Vision) in December 2004.

B.P. Amavasai, F. Caparrelli, A. Selvan, M. Boissenin, J.R. Travis and S. Meikle. Machine vision methods for autonomous micro-robotic systems. In Kybernetes Journal, vol. 34 no. 9/10 2005, ISSN 0368-492X.

Stuart Meikle, B.P. Amavasai and F. Caparrelli. Towards Real-Time Object Recognition using Pairs of Lines. In Real-Time Imaging, Elsevier Journal, vol. 11 (2005) 31-43.

Jan Wedekind, Manuel Boissenin, Balasundram P. Amavasai, Fabio Caparrelli, and Jon Travis. 3-D/4-DoF Real-Time Object Recognition in a Microscopic Environment Using Geometric Hashing. Submitted to the 9th European Conference on Computer Vision. Graz, Austria, May 7 - 13, 2006.

Manuel Boissenin, Jan Wedekind, Bala Amavasai, Fabio Caparrelli, Jon Travis. Stencil tracking: a Hough transform based tracker. Submitted to the 9th European Conference on Computer Vision. Graz, Austria, May 7 - 13, 2006.

Anna Eisinberg, Keith Houston, Fabio Caparrelli, Balasundram Amavasai, Manuel Boissenin, Paolo Dario. Marking techniques for vision recognition of microgrippers for micromanipulation. Submitted to IEEE International Conference on Robotics and Automation (ICRA2006). Orlando, Florida, May 15-19, 2006.

8.6 Disseminations by UNIKARL

R. Estaña and H. Wörn: High precise Microrobot Navigation with a Moiré-based Position sensing System; Technisches Messen 71, 2004, pp 545 – 549 (German)

R. Estaña and H. Wörn: Moiré-based positioning system for small micromanipulation units. In Optical and Microtechnology Products Conference, volume 1, OMP OPTO MICRO PRODUCTS}, pages 75 - 81. AMA Service GmbH, AMA Service GmbH, May 2004.

R. Estaña, J. Seyfried, F. Schmoeckel, M. Thiel, A. Buerkle, and H. Wörn: Exploring the Micro- and Nanoworld with centimetre-sized autonomous microrobots. Industrial Robot, 31(2):159 -- 178, February 2004.

H. Wörn, J. Seyfried, A. Bürkle, R. Estaña, F. Schmoeckel, M. Thiel: Kubikzentimeter-große autonome Mikroroboter für die Mikro- und Nanowelt, 2003, Published in „Autonome mobile Systeme 2003, Informatik aktuell, Springer Verlag", Pages 281-291

Jörg Seyfried, Ramon Estaña, Ferdinand Schmoeckel, Michael Thiel, Axel Bürkle, Heinz Wörn: "Controlling cm^3 sized autonomous micro robots operating in the micro and nano world"; Published: in Proc. 6th Int. Conf. Climbing and Walking Robots and their Supporting Technologies (CLAWAR 2003), Pages: 627-634

Patent: A German patent on the GPS-System has been filed.

Title: " Moiré-basiertes hochgenaues Positions-Messsystem " (Translation: "Moiré-based high-precise position sensing system")

8.7 Disseminations by SSSA

8.7.1 Papers submitted to Journal:

A. Menciassi, A. Eisinberg, I. Izzo, P. Dario, "From "Macro" to "Micro" Manipulation: Models and Experiments" submitted to IEEE Trans. Mech. (Focused Section on Micro and Nano Manipulations) on 29/09/2002

A. Eisinberg, P. Valdastri, I. Izzo, A. Menciassi, P. Dario, "Design of a microsensor for the measurement of mechanical tension from resistance blood vessel" submitted to BioSystem, Elsevier on 09/03/2003, notification of acceptance: 28/05/2003.

8.7.2 Papers submitted to Conference:

"Design and Shape Deposition Manufacturing (SDM) Fabrication of a PZT-actuated Tool for Micromanipulation" , CIRA 2005 , Helsinki, Finland, 27/05/2005

A. Eisinberg, P. Valdastri, I. Izzo, A. Menciassi, P. Dario, "A portable and sensorized μelectro discharge machined microgripper for micromanipulation of biological tissues", submitted to IROS 2003.

8.8 Disseminations by UB

8.8.1 2006 Presented conference abstracts

J. Otero, A. Saiz, J. Brufau, J. Colomer, R. Ruíz, J. López, P. Miribel, M. Puig, J. Samitier; "Reduced Dimensions Autonomous AFM System for working in Microbiorobotics" BioRob 2006. The first IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics.Pisa, Tuscany, Italy. February 20-22, 2006

R. Casanova, A. Saiz, A. Arbat, J. Colomer, P. Miribel, A. Diéguez, M.Puig and J.Samitier, "Integrated Electronics for a 1cm^3 Robot for Micro and NanoManipulation Applications: MiCRoN"; BioRob 2006. The first IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics.Pisa, Tuscany, Italy. February 20-22, 2006

J. Otero, J. Brufau, A. Saiz, R. Casanova, R. Ruiz, J. López, P. Miribel, A. Diéguez, M. Puig, J. Samitier; "Electronic Modules for an Autonomous Microrobot for Cell Micro-Nanomanipulation"; BioRob 2006. The first IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics.Pisa, Tuscany, Italy. February 20-22, 2006

8.8.2 2005 Conference publications

Casanova, R.; Dieguez, A.; Lacort, J.; Nierlich, M.; Steinmetz, O.; Arbat, A.; Samitier, J.; "A digital control circuit for a biomedical robot"**;** Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2005; ISBN: 0-7803-9446-1, pp. 381-387; Sofia (BULGARIA)

Lacort, J.; Casanova, R.; Arbat, A.; Dieguez, A.; Brufau, J.; Lopez, J.; Samitier, J.; "An integrated controller for a AFM tool mounted in a wireless microrobot."**;** Conference on Design of Circuits and Integrated Systems, DCIS 2005; Lisboa (PORTUGAL)

Lacort, J.; Casanova, R.; Brufau, J.; Arbat, A.; Dieguez, A.; Nierlich, M.; Steinmetz, O.; Puig, M.; Samitier, J.; "An integrated controller for a flexible and wireless Atomic Force Microscopy."; Microtechnologies for the new millenium 2005.; Sevilla (Spain)

Brufau-Penella, J.; Puig-Vidal, M.; López-Sánchez, J.; Samitier, J.; Driesen, W.; Breguet, J.M.; Gao, J.; Velten, T.; Seyfried, J.; Estaña, R.; Woern, H.; "MiCRoN: small autonomous robot for cell manipulation applications."; IEEE International conference on Robotics and Automation ICRA 2005; Barcelona (Spain)

F. Tagliareni, M. Nierlich, O. Steinmetz, T. Velten J. Brufau, J. López-Sánchez, M. Puig-Vidal, J. Samitier; "Manipulating biological cells with a micro-robot cluster**;** International Conference on Intelligent robots and systems IROS 2005**:** ISBN 0-7803-8912-3 , pp. 426-431;Alberta (CANADA)

Brufau-Penella, J.; Ruiz-Montero, R.; Otero, J.; López-Sánchez, J.; Puig-Vidal, M.; Samitier, J.; **“** Diseño de un cabezal AFM como herramienta de un microrobot de reducidas dimensiones”; Annual seminar on automatic control, industrial electronics and instrumentation SAEEI 2005; Santander (Spain)

A.Saiz-Vela, P.Miribel-Català, J.Colomer, M.Puig-Vidal, J.Samitier, “*Towards an Efficient Integrated Power Supply and Driving System for Battery Powered Microrobots”,* Proceedings of the XX Conference on Design of Circuits and Integrated Systems, DCIS 2005, (Lisboa, Portugal),

J. Brufau-Penella, A. Saiz-Vela, J. Otero, J. López-Sánchez, P. Miribel-Català, M. Puig-Vidal, J. Samitier, “*Autonomous Atomic Force Microscopy System based on self-sensing AFM probes” ,* Proceedings of the XX Conference on Design of Circuits and Integrated Systems, DCIS 2005, (Lisboa, Portugal),

R. Casanova, A. Saiz, J. Lacort, J. Brufau, A. Arbat, A. Diéguez, P. Miribel, M. Puig, J. Samitier, “*Towards Cooperative Autonomous and Intelligent* $1cm^3$ *Robots for Micro and NanoManipulation Applications: MiCRoN*”, Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2005, ISBN: 0-7803-8912-3, pp. 760-765

A. Saiz-Vela, P. Miribel-Català, M. Puig-Vidal, J. Samitier, “*An Efficient 2-stage Fractional Charge Pump based on Frequency Regulation*” Proceedings of SPIE International Symposium on Microtechnologies for the New Millennium 2005 (VLSI Circuits and Systems II conference), (Sevilla, Spain), ISBN: 0-8194-5832-5, vol. 5837, pp. 166-173

A. Saiz-Vela, P. Miribel-Català, M. Puig-Vidal, J. Samitier, “*An Electron Mobility Independent Pulse Skipping Regulator for a Programmable CMOS Charge Pump”* Proceedings of IEEE International Symposium on Circuits and Systems, ISCAS 2005, (Kobe, Japan), ISBN: 0-7803-8834-8, pp. 117-120

8.8.3 2004 Conference publications

Casanova, R.; Diéguez, A.; Lacort, J.; Samitier, J.; “Hardware implementation of the Bresenham line generation algorithm applied to micro-robot movement.”; XIX Conference on Design of Circuits and Integrated Systems. DCIS 2004**;** November 24-26. Pages: 40; Bordeaux (France)

A. Saiz-Vela, P. Miribel-Català, J. Brufau, R.Casanova, M. Puig-Vidal, J. Samitier, “*Specific Drivers and Integrated 20V Regulated Charge Pump for an Autonomous MicroRobot: MiCRoN”,* Proceedings of the XIX Conference on Design of Circuits and Integrated Systems, DCIS 2004, (Bordeaux, France), ISBN: 2-9522971-0-X, pp. 348-353, 2004

R. Casanova, P. Miribel-Català, A. Saiz-Vela, M. Puig-Vidal, J. Samitier, “*Design of a Step-up* 111H*400mW@40V Charge Pump for Microrobotics Applications in a 100V-0.7um Intelligent Interface Technology”*, Proceedings of the IEEE International Symposium on Industrial Electronics, ISIE 2004, (Ajaccio, France), ISBN: 0-7803-8304-4, pp. 1227-1229, 2004

A. Saiz-Vela, P. Miribel, R. Casanova, M. Puig-Vidal, J. Samitier, "*Disseny de circuits analògics CMOS per comanda d'actuadors i gestió energètica en microrobots autònoms*", IV Jornades de recerca en enginyeria biomèdica, JEBC'04, (Barcelona, Spain), ISBN: 84-688-6747-0, pp. 309-314, 2004

Brufau-Penella, J.; Garcia-Vázquez, I.; López-Sánchez, J.; Puig-Vidal, M.; Samitier, J.; "Sistemes d'actuació i control per a un capçal AFM d'un microrobot amb sensor de força integrat"; IV Jornades de recerca en enginyeria biomèdica, JEBC 2004; ISBN:84-688-6747-0 pp,301-307**;** Barcelona (Spain)

Brufau-Penella, J.; López-Sánchez, J.; Puig-Vidal, M.; Samitier, J.; "Implementacion de un sistema electrónico para un microrobot autónomo en aplicaciones biomédicas."; Annual seminar on automatic control, industrial electronics and instrumentation SAEEI 2004; Toulouse (France).