Development of Miniature Manipulators for Applications in Biology and Nanotechnologies

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Abstract
In the precision engineering industry, research and development is undertaken towards the development of microfactories, miniaturized environments for fabrication and assembly of small components. Microhandling and micromanipulation, especially in biology, but also in other fields, often require dedicated devices and special environments (pressure, humidity and temperature controlled) as well. It would be a logical step to miniaturize micromanipulation and micro handling devices to a certain extent in a similar manner as tools and environments, with the same advantages as microfactories have for manufacturing: lower energy consumption, better control of the operation environment and smaller space required for an entire laboratory. This paper presents several miniature positioning and manipulation devices based on piezoelectric transducers, which can serve to build a “Microfactory” for application in Microbiology for either telemanipulation or semi- and fully autonomous manipulation. The proposed devices employ an amplification of the piezoelectric motion with bimorph, monolithic flexure bridges or inertial principles.

1 Introduction
The trend towards miniaturization of products has marked the electronics, precision engineering and optics industries for the past decades. Consequently, there is also a trend towards miniaturization of the tools used for the fabrication of the small components. The tools often occupy a considerable space and often necessitate important efforts to guarantee certain operation conditions, such as clean environment or a constant temperature. Microfactories are space and energy saving systems for the fabrication of micromechanical, microelectromechanical or microoptical components. The term was coined by researchers at the Mechanical Engineering Laboratory in Tsukuba some years ago (nowadays AIST National Institute of Advanced Industrial Science and
Technology), which realized a first microfactory prototype with components such as micro lathe, micro press and micro manipulator.

This paper presents systems for micropositioning and micromanipulation, which not only bring additional functionality to a certain number of existing systems, but also represent new solutions at lower cost and with a smaller size. We introduce miniature xy-stages for positioning of samples under optical and scanning probe microscopes, as well as systems for micromanipulation. At first, a brief explanation on the requirements for instruments in micromanipulation is given, as well as an overview on common amplification principles for piezoelectric motion. In the following, several linear positioners using bimorph and monolithic piezoelectric elements are presented, followed by systems based on the stick-slip effect and finally developments for an autonomous micro handling platform based on mobile microrobots.

2 Devices for Micromanipulation

For cell manipulation there is a number of different typical micromanipulation tasks. For \textit{in vitro fertilization}, the egg cell is held with a holding pipette, while another (sharp) pipette is used to penetrate the cell membrane and inject a sperm cell. \textit{DNA injection} or cell injection ("cloning") requires to hold the egg cell, and a second pipette is used to inject DNA material into the cell, requiring similar tools as for fertilization. Other methods require the nucleus to be removed by opening the cell using a needle, removing a part of the cytoplasm containing the nucleus (enucleation) and injecting cell substrate from other cells (nuclear donors) into the cell using a pipette. Two more tools are needed, as an electric field has to be applied over the cell for activation and fusion.

\textit{Patch clamp} techniques are methods to record single ion-channel currents or currents from entire small cells. Glass pipettes are used as "electrodes", which are applied to cell membranes to record the currents. \textit{AFM systems} are used to measure cell properties, such as elasticity of the cell membranes.

Micromanipulation setups usually consist of 3 dof linear positioners, which carry the appropriate micromanipulation tools, such as for instance needles or micro pipettes. The positioners for the tools are either motorized or manually operated with a lever or hydraulic reduction systems. The operation range is in the order of some mm for hydraulic manipulation systems or some cm for motorized or screw driven systems. In hydraulic positioners, the polymer tubes used between positioner and the manual or motorized screw prevent the transmission of vibration from the screw to the micromanipulator. The reduction of the movement is typically up to 100 times. Another way to position micromanipulators are custom designed motors in combination with precision roller bearing slides, which may have resolutions better than 1µm depending on the resolution of the encoder which is used for position control.
Manual positioning stages or motorized stages with resolutions of 0.5 ~ 1µm are usually employed to position the petri dishes or supports containing the samples. Alternatively, a lever mechanism is sometimes used as a low-cost solution to obtain a fine positioning. For these mechanisms, the resolution and accuracy strongly depend on the skills of the user.

3 Piezoelectric Micromanipulators - A Short Overview

Piezoceramics are very well suited to replace manual positioning elements as well as motorized systems. The resolution can be increased, and the overall size of the system becomes smaller. As piezoelectric transducers have very small deformations, which are in the order of about 0.1% of the actuator length or less for applied voltages of 100 V, a mechanical amplification of the motion is often used.

Many principles are known to amplify the deformation of piezoelectric actuators, and often several amplification methods are combined. Table 1 resumes some of the common methods. Especially Inchworm Microdrive Systems and Impact Drive systems have been used in microbiology applications, the Inchworm for the possible smooth motion, and the impact drive as the high accelerations permit to penetrate cell membranes with minimum damage.

In the following, we will especially focus on applications of bimorph elements for positioning applications with a small range and stick-slip applications for devices requiring a larger range, both especially because of the potential for miniaturization of the handling devices.
<table>
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<th>Principle</th>
<th>Range</th>
<th>Resolution</th>
<th>Remarks</th>
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<tr>
<td>Piezoelectric element without amplification</td>
<td>0.05 ~ 0.5µm</td>
<td>0.01 ~ 0.1nm</td>
<td>Transversal, axial or shearing mode, shearing mode yields the largest deformation</td>
</tr>
<tr>
<td>Stack (Multilayer)</td>
<td>2 ~ 20µm</td>
<td>0.5 ~ 0.5 nm</td>
<td>large electric capacitances, expensive</td>
</tr>
<tr>
<td>Bimorph or Monomorph</td>
<td>50 ~ 1000µm</td>
<td>10 ~ 250nm</td>
<td>low forces and low resonance frequencies</td>
</tr>
<tr>
<td>Monolithic flexure bridges [1]</td>
<td>1 ~ 5µm</td>
<td>0.2 ~ 2 nm</td>
<td>“Monolithic Piezoelectric Actuator” (MPA) - low forces, fragile</td>
</tr>
<tr>
<td>Ultrasonic motors [2]</td>
<td>some cm</td>
<td>50 ~ 500nm</td>
<td>large thrust forces</td>
</tr>
<tr>
<td>Inchworm®-motor [3]</td>
<td>some cm</td>
<td>≤ 1 nm</td>
<td>large thrust forces, 3 actuators are required, expensive</td>
</tr>
<tr>
<td>Walking drives [4, 5]</td>
<td>some cm</td>
<td>0.1 ~ 10 nm depending on the actuator type used (simple element or bending actuator)</td>
<td>two or more actuators required</td>
</tr>
<tr>
<td>Impact drives [6, 7]</td>
<td>some cm</td>
<td>some nm (depends on the masses, surface quality, actuator)</td>
<td>very simple, resolution limited to the size of one step</td>
</tr>
<tr>
<td>Stick-slip [8, 9, 10]</td>
<td>some cm</td>
<td>≤ 1 nm</td>
<td>very simple</td>
</tr>
</tbody>
</table>

Table 1: Comparison of positioning ranges and resolutions of piezoelectric actuators with amplification, with linear actuators in the upper section and piezoelectric motors in the lower section
4 Miniature Linear Positioners

Scanning Probe Microscopy (SPM) is a powerful tool frequently used in biology [11]. The most popular device is certainly the Atomic Force Microscope (AFM). In an AFM, the probe is a very sharp tip attached to a cantilever that is scanned over the sample. The atomic forces between the probe and the sample are monitored giving information on the sample topography. Under certain conditions atomic lateral resolution is achieved.

Various systems are applied for the scanning stages. Piezo-electric tube elements are frequently used, allowing scanning area of several square microns, depending on their size and length [12, 13]. Less frequent, but with potentially larger scanning area up to of few square millimeters, are the scanners based on electromagnetic motors, usually voice coil motors [14]. The commercial products tend to be rather bulky and are difficult to be integrated into existing systems. Scanners based on piezoelectric transducers have an insufficient workspace, particularly for biology applications where a range of several tens of microns is necessary. Voice coil based scanners require an advanced control system and, in most cases, position sensors, making the device bulky and expensive.

In this section, we present two types of scanning stages. The first one was designed to obtain a device extremely thin and simple, thus having a complete AFM with a total thickness of about two millimeters. Because of its shape it has been named the Credit Card AFM (CCAFM) [15]. The second stage was especially designed to fit in an existing instrument developed by the University of North Carolina (UNC) [16].

4.1 X-Y Scanning Stage with Monolithic Piezoelectric Actuators (MPA)

4.1.1 Operating Principle

This scanning stage (figure 1) is cut directly out of a single plate of piezoelectric ceramic (PZT). Typical dimensions are 25x21x1 mm$^3$ for a scanning area of 10x10 µm$^2$.

The stage consists of two monolithically fabricated flexure bridges (monolithic piezoelectric actuators, MPA). A MPA is cut in a way that the actuating parts, supporting elements and hinges are arranged to amplify the motion by a buckling effect as shown in figure 2. The electrodes have to be patterned, resulting in regions that can selectively be activated or deactivated. Figure 2a and 2b show one of these actuators and a detail of the hinge, respectively. In the complete system two similar systems are used. A lever converts the rotation $\Delta \alpha$ into a linear motion of the output of the stage.

On the one hand motion amplification increases for smaller $d_e$. On the other hand, this will increase the internal stresses resulting in forces opposing the piezo motion. Therefore an optimal $d_e$ exists that gives a maximum
Figure 1: A prototype of the X-Y Scanning Stage with Monolithic Piezo Actuators

Figure 2: Monolithic Piezoelectric Actuator a), detail of the notch hinge b) with their characteristic dimensions

Figure 3a shows the dependency of the displacement versus $d_e$ width of the hinge with $e_c$ being the independent parameter. The optimum $d_e$, in this case 0.7mm, is independent of $e_c$. Not surprisingly and in accordance with equation 1, the displacement varies linearly with the piezoelectric coefficient $d_{31}$ (figure 3b). The Young modulus of the piezoceramic material has no influence on $\Delta h$. 

The displacement $\Delta h$ can be calculated in function of the characteristic dimensions of the actuators [17]

$$
\Delta h \approx \frac{-2d_{31}(d - r_c)l}{2t \pi \sqrt{\frac{e_c}{r_c}}} \left[ \frac{3d}{w_1^3d_e} + \frac{12r_d}{w_1^3} + \frac{36r^2d}{w_1^3d_e} + \frac{3(d-r_c)}{(d_e+2r_c+e_c)d_e} \right] + d_e l
$$

(1)

where $d_{31}$, $U$ and $l$ are the piezoelectric coefficient, the applied voltage and the arm’s length, respectively (figure 2).

The width of the hinge $e_c$ cannot be arbitrarily thin for robustness reasons. The prototype has a hinge of 250µm. By optimizing $d_e$ typically a 20-fold amplification of the piezoelectric movement can achieved (figure 3).
4.1.2 Experimental Results

Several prototypes with $d_e$ varying from 0.2 mm to 1 mm (for the used material PIC 151 the piezoelectric coefficient is $d_{31} = -210 \times 10^{-12} \text{m/V}$) were tested in the laboratory. Figure 4a compares experimental results with equation 1. Figure 4b to 4d show the quasi-static hysteresis curve, the harmonic and step responses of the prototype with $d_e = 0.7$ mm, respectively.

A sample with a 158 nm pitch reference grid was fixed on the output of the x-y scanning stage and images were taken with an AFM cantilever mounted on a linear axis. Figure 4a shows an important cross coupling of about 40% between x and y axes. With an appropriate control law it can be compensated (figure 4b) [17].

4.2 X-Y Scanning Stage with Bimorph Piezo Actuators

4.2.1 Application

A team from the National Research Resource of the UNC in Chapel Hill (USA) developed a particular 3D Magnetic Force Microscope (3DFM) to measure the viscosity of a cell. A tiny magnetic sphere is introduced into the cell. The sphere is kept in place by magnetic forces while the cell moves. The viscosity is derived from the magnetic forces needed to keep the sphere stationary. These forces are controlled and measured by a close-loop control system [16].

In the UNC set up, the displacement of the cell was obtained by using a commercial X-Y mechanical stage. Despite its outstanding quality, the stage has several drawbacks: its is bulky, its bandwidth and position resolution are too small and it contains large metallic parts perturbing the UNC instrument.
**Figure 4:** a) Comparison of measured values with prototypes having $d_e$ varying from 0.2 mm to 1 mm to a calculation according to equation 1, b) quasi-static hysteresis curve, c) the harmonic and d) step responses of the prototype with $d_e = 0.7\, \text{mm}$.

**Figure 5:** Compensation of the coupling between the axes, a) scanned sample without correction, b) with correction. The scanned area is about $2\, \mu\text{m}^2$ and the grating 158 nm.
LSRO was thus asked to develop a custom scanning stage that fulfills UNC special requirements, one of the most challenging being the size constraints, especially in thickness (figure 6).

### 4.2.2 X-Y Stage Prototype

The developed stage consists of two bimorph actuators. The actuators are fixed to a base on the one end. On the other end they are interconnected by a flexible structure made of aluminum. This structure transmits the displacement of the bimorph elements in the working spot. A parallelogram in one of the two arms prevents the rotation of the spot. The overall dimensions are 40x40x4 mm$^3$ for a scanning range of ±56µm$^2$ for an operating voltage of ±200V. A bandwidth of more than 700Hz is achieved.

The bimorph elements are composed of two 0.5mm thick piezoelectric layers with a 0.25mm Al$_2$O$_3$ ceramic sheets sandwiched between them to improve the robustness of the system (figure 7). The free displacement calculated for the prototype dimensions is ±63µm. Once assembled, this value is strongly reduced by the metallic parts and elastic forces opposing the bimorph movement. A model of the stage considering these forces has been established in
Figure 8: The first three modes of vibration of the xy-stage; the left two modes have to be considered to determine the shaper.

[18]. The final range of the prototype is ±56µm at ±200V.

4.2.3 Dynamic Performances of the Stage and Improvements

As the natural frequencies of the proposed stage and similar bimorph-based systems are low (below 1kHz), unwanted dynamics of the stage are often a problem, especially for scanning motion with high frequency, but also if trajectories have to be followed with high velocities. A possibility to eliminate vibration consists in “breaking” an input step into a staircase-shaped signals as described in [19].

Based on this idea, especially in the past 15 years methods have been proposed which are commonly called “input shaping” or “command shaping”[20, 21]. Sequences of two or more pulses are convolved with the system command. The pulse amplitudes and delays are determined by the damped natural frequencies \( w_{di} \) and damping coefficients \( \zeta_i \) of the system. With a properly dimensioned shaper, it is possible to suppress residual vibration with only two pulses, if \( w_{di} \) and \( \zeta_i \) are known.

Figure 8 shows the first three vibration modes. The first two modes (left and middle), are very close. Because of the coupling of both actuators both frequencies\(^1\), must be considered, if vibration is to be suppressed successfully. From the step response of the system, figure 9 measured on one axis, we obtain the natural frequencies. Besides of these two vibration modes, there is an off-plane vibration of the metallic structure, as visible in figure 8, right.

Multiple modes can be suppressed with several strategies. The signal can be convolved with the pulses suppressing each resonance at once or by applying a shaper for one natural frequency before applying the second sequence. In the particular case of the x-y stage, the shapers for the two different modes

\(^1\)The natural frequencies can be extracted from the graph 9 using the relation \( \sin(At) + \sin(Bt) = 2\sin\left(\frac{A+B}{2}\right)\cos\left(\frac{A-B}{2}\right) \).
Figure 9: Step response of the xy stage shown in fig 6, taken with a 40V step input.

Figure 10: Measured input signals and responses, (a) unshaped square wave, (b) shaped square wave, for each graph system input and response superposed, comparison of the trajectory following capabilities between unshaped (c) and shaped (d) signal
were applied to the same signal, and the sum of both shaped signals was used to drive the system.

The amplitudes for a simple two-pulse shaper and the delay for the second pulse have been determined from graph 9 and yield a good improvement of the settling time. However, a small experimental adjustment of the amplitudes still slightly improved the vibration suppression.

Figure 10 shows the comparison between the step responses of an axis of the system for an unshaped signal and a shaped signal.

A small vibration amplitude remains, which has to be explained with the presence of superposed higher vibration modes. Particularly the mode depicted in figure 8, right, which is very close to the other modes, influences the accuracy of the determination of the natural frequencies. A simple two-pulse shaper will therefore not completely suppress vibration, as it is very sensitive to modeling errors.

Shapers with three or more pulses might suppress the residual vibration more efficiently, but will considerably increase the length of the command sent to the system and thus the phase lag between in- and output. A different mechanical design is supposed to raise this resonant frequency considerably which seems to be a more efficient way to suppress this vibration.

4.2.4 System Integration

The X-Y stage has been successful implemented into the 3D magnetic microscope at UNC (figure 11 a)

Figure 11 shows the stage mounted on the commercial “Mad City Labs” stage on a newly designed 3DFM system for use in validating the tracking algorithms. The LSRO stage is driven with a stimulus sine-wave whose frequency is swept, and determined how well the tracking algorithm can keep up with the bead that is moved by this stimulus.
The stage being vacuum compatible, it has also been tested in a SEM chamber. Furthermore, it has been used to replace the existing scanner of an AFM in order to get a much larger scan range, going from the actual $5\mu m^2$ to more than $50\mu m^2$.

**4.3 Micro Manipulators based on PZT-Actuators - an Example**

Handling of small objects such as cells often requires more than two degrees of freedom. Manipulation stages are usually combined serially to obtain the necessary movements. If two needles or other tools are situated very closely together, the bulkiness of the common serial manipulators may be a problem. An interesting approach has been proposed by Tanikawa and Arai [22], Two parallel platforms based on piezoelectric stack elements with 6 degrees of freedom for each platform are built, with the lower platform used to position both tools and the upper platform used to position one tool with respect to the other. Later publications used the “delta” kinematic structure with 3dof per platform [23].

A more simple manipulation tool with 3dof and a very small number of components has been developed, which serves to position microtools. A monomorph disk with three patterned electrodes is used, the steel shim on the other side serves at the same time as ground electrode and as protection. An axial motion of the tool is performed, if the same voltage is applied to all electrodes. By applying different voltages the central spot inclines depending on the amplitude (figure 12a). This inclination is amplified by the length of the tool in use. Therefore the system has to be re-calibrated upon tool changes.

*Figure 12: a) and b) functioning principle of the 3dof manipulator based on a patterned monomorph disk, c) prototype with two tools (microneedle and micropipette), the disks have diameters of 25mm*
Using two similar disks as shown in figure 12 allows to grip microscopic objects. The adjustment in the axial direction of the tools, which is necessary to obtain the same length of the tools has been done by attaching a miniature stick-slip drive to the disk. For the disk diameters of 25mm and thicknesses of the disks of 0.5mm PZT and 0.15mm stainless steel, axial displacements of about $25\mu m$ can be obtained. For the “x” and “y” motion resulting from the tilt of the central spot the displacements depend on the length of the tool, more than $50\mu m$ can be easily achieved.

5 Miniature Positioners With Long Ranges - Stick-Slip Drives

For micro positioning applications, where a high resolution at a long range is needed without necessity of large force generation capabilities, such as e.g. cell handling, stick-slip actuators fit very well. In stick-slip actuators or inertial drives, guiding and actuating functions are combined, which results in systems with a very small number of components allowing for a miniaturization of the system.

A slider or inertial mass is in contact with guiding elements attached to the piezoelectric transducer(s). The Piezoelectric transducers are driven with an asymmetric voltage signal, which causes a rapid displacement of the guiding element in one direction and a slow displacement in the other direction. During the slow deformation the slider sticks to the guiding element, and it slides during the rapid deformation, which will cause a net movement. Stick-slip systems allow to seamlessly switch between the so-called stepping mode with alternating slow and fast deformation of the piezoelectric element, and the scanning mode in which the system behaves like a linear piezoelectric positioner with the resolution only being limited by the resolution of the driving circuitry and the sensor used for feedback.

Depending on the required resolution and step size, several actuator elements can be used for stick-slip systems. Shear mode elements [9, 10], tube-shaped actuators [8, 24, 9, 25] or transversal and axial multilayer piezoelectric elements [26, 27] have been proposed in the past. Transversal or shearing mode actuators allow for the conception of very compact systems with step sized between $0.1$ and $1\mu m$ and are therefore preferably used for miniature systems.

In the following, two examples of positioning systems for operation under the microscope suitable for manual or semiautonomous operation will be given, followed by miniaturized robotic platforms for a fully autonomous micromanipulation.
5.1 2DOF and 3DOF - Positioners Based on the Stick-Slip Principle

Stick-slip driven systems have a high potential for many applications where traditionally either motorized or manual micropositioning systems have been used and where a higher precision and a smaller volume of the system is required. A typical example are positioning stages for microscopes. Several positioning stages adapted to specific applications and experimental environments have been developed at LSRO. A particular advantage of stick-slip drives replacing screws and motors is the possibility to easily position stages manually and to do only the high resolution positioning with the piezoelectric elements.

Figure 13 shows a stage developed for cell manipulation, which is based on a very simple cinematic structure; 3 legs are deformable in two orthogonal directions and drive the stage. This kinematic has the advantage to permit a very compact and flat design: the whole stage is about 10mm thick and 90mm x 90mm large, and other components as heater and temperature sensor have been integrated and the design was made to permit a change of the lenses without changing the position in vertical direction. With a small number of components a stage with about 230nm resolution in the stepping mode has been realized, which is sufficient for optical microscopy. If the piezoelectric elements are controlled in the scanning mode, the resolution is virtually unlimited.

The design does still permit an uncontrolled rotation, although for positioning of microscopic samples this can often been tolerated. If rotation has to be prevented without unnecessarily complicating the control, a serial kinematic design has to be favored. An x-y stage and a micromanipulator based on a serial kinematic design have been developed as well (figure 14). A sym-
metric motion in vertical direction is possible due to a gravity compensation by a spring.

5.2 Miniaturization of Actuators for Stick-Slip Drives

5.2.1 Monolithic miniature “push-pull” actuators

Assembly is often a critical point for miniature systems. The previously shown stick-slip driven systems are still assembled from individual components. For further miniaturization, a new kind of monolithic piezoelectric actuator based on the “push-pull” principle has been developed [28]. It allows to integrate a number of actuators into the same piezoceramic substrate only by patterning the electrodes. The deformations obtained with the proposed elements are in the order of some 100 nm for commonly available piezoelectric materials and dimensions of some mm.

Two or more electrodes are patterned on a PZT-sheet, and neighboring regions are operated inversely. As one zone of the substrate expands and the other contracts, a lateral movement is generated, which can be exploited with a guide element attached to the zone between the electrodes (Fig 15).

The opposite deformation in the two neighboring regions can be obtained by applying opposite voltages on the two electrodes. This will cause a transversal contraction in one zone of the bulk, and an extension in the other one (figure 15, left). To further simplify, it is also possible to create these two regions by applying different voltages during the poling procedure to the previously patterned electrodes. For driving, the same voltage is applied on both electrodes in order to obtain a similar “push-pull” movement (Fig 15, right).

The neighboring zones can be simply patterned on a sheet of piezoelectric...
Figure 15: Functioning principles using two different voltages (left) or two different poling directions (right).

material (figure 16) by either screen printing, lift-off or other patterning techniques. No machining of the bulk material is required. By arranging several of these electrode pattern on one PZT bulk material, multiple actuators can be integrated on the same piezoelectric substrate, allowing the design of systems with up to 3DOF or to integrate the required number of actuators working in parallel, such as for a linear axis as shown in the following subsection.

A two-dimensional motion of one point can be generated, if the pattern is located at the edges of the bulk material. The first of the two orthogonal displacements is obtained by applying voltages generating an electric field in the same direction on both electrodes, and the other by inverting the polarity on one of the electrodes.

The major advantages of this kind of actuator are simplicity, robustness, high resonance frequencies and the relatively simple fabrication process.

5.2.2 An Application Example

A simple application of these actuators is the linear stage shown on figure 17. It has a range of 8mm and an actuator stroke of 200nm. The same electrode shape as shown on figure 16 has been used for this stage. A particular point is that the sectioned electrodes have been used for poling. For operation all electrodes on either side are short-circuitied, which allows to operate the stage with two power supply cables like any other piezoelectric element. Velocities of up to $4\,\frac{mm}{s}$ have been obtained with this device with step sizes of more than 200nm for an electrode diameter of 5mm and operation voltages of ±150V.
**Figure 16:** Functioning principle of the monolithic “push-pull” actuator, the dotted line represents the deformation of the zones delimited by the electrodes if a voltage is applied (patent pending)

**Figure 17:** Design of a linear stage based on the push-pull principle. A minimal number of components is required, and only two wires as for any other piezoelectric positioner are needed, as the neighboring electrodes are poled inversely. Velocities of up to $4 \text{ mm/s}$ have been measured at about $19kHz$. 
6 An Autonomous Handling System Based on Mobile Robots and Miniature Tools

6.1 MiCRoN - an Autonomous Micro Handling Platform

With smaller systems and the integration of multiple handling agents into the same “Microlab”, the development of autonomous agents becomes important. Several research groups have addressed the issue of autonomous micromanipulation. On the one hand, autonomous or teleoperated systems have been proposed [29, 30]. On the other hand, microrobots, i.e. robots capable of performing precise movements and having very small dimensions, have been developed [31, 32] for manipulation. The microrobots are usually still tethered and controlled by a host system.

In a joint effort of 7 European research institutes with renowned expertise in the field of microrobotics, a EU-sponsored project has been launched in 2002, which aims to go one step further. The objective of the MiCRoN-project\(^2\) is to provide a new approach to micro-manipulation by developing a multi-microrobot manipulation system prototype to handle \(\mu\)m-sized objects or even nano-scale objects. The advantage of a cluster of microrobotic agents is to use a number of relatively simple systems working in cooperation and thus permitting more complex manipulation tasks.

The system will consist of a cluster of between 5 and 10 small mobile autonomous robots, each having a volume of about \(1cm^3\). These wireless agents co-operate within a desktop environment to execute a range of tasks associated with manipulation and assembly from the nano- to the micro-range. The proposed system comprises several essential subsystems such as a global positioning system to provide accurate position information (resolution \(\sim 1\mu m\)) of each microrobot, advanced manipulation tools and a wireless power supply unit. It also includes user interfaces as well as systems for transporting \(\mu\)m-sized objects into and out of the working range of the robots.

Potential applications have been identified, and besides microassembly and sample handling for TEM microscopy these are cell manipulations and particularly the study of neuronal cells using probes as used in scanning microscopy and other microfabricated tools.

6.2 Components for the MiCRoN Micro Handling platform

6.2.1 Structure of the system

A modular approach has been chosen for the robot design. One robotic agent consists essentially of

- Piezoelectric locomotion system (“carrier”)
- Control electronics and communication unit

\(^2\)“Miniaturized Co-operative Robots advancing towards the Nano range”
• Power electronics
• Tool(s), such as grippers, needles etc.
• Power transmission system
• Energy storage unit

The micromanipulation platform as a whole consists of

• A workspace with power transmission elements (power floor, 500mm x 500mm)
• The robotic agents (5-10)
• Dedicated (larger) robots carrying local vision systems
• Global vision system
• Communication unit
• Host computer for supervision

The main challenge for autonomous agents is the power autonomy, as the required nanometric resolution cannot be obtained with miniature electromagnetic motors, and piezoelectric elements are used. Power requirements for tools and the transmission of information have to be considered as well. The first concepts of the system needed more than 1W, thus battery-powered solutions were excluded. A power supply based on induction (power-floor) has been proposed with a small energy buffer or battery supply “on-board”. The onboard supply becomes necessary, as it will not be possible to continuously power the agents. Certain dead zones have to be overcome, and some of the applications require the power supply to be switched off temporarily because of the electromagnetic perturbations.

A high effort has been made to reduce power requirement of the robots. In the present state, depending on the operation mode (high autonomy or high velocity) autonomy of almost one-hour using button batteries will be possible.

6.2.2 Locomotion modules

One of the modules integrated in the robot is the locomotion platform that provides the robot with a controlled nanometric motion in three degrees of freedom (X,Y,\(\theta_z\)). Several carrier module prototypes have been developed. They function either on a walking motion or on the stick-slip driving principle. During the development of these prototypes, special care has been given to design for assembly and fabrication, in order to allow the possibility to step up to low and medium batch size fabrication.

For the prototypes based on the stick-slip principle, three of the monolithic “push-pull” actuators explained above are integrated into a piezoelectric sheet, resulting in a micro robotic locomotion platform. A first prototype that has been developed with this technology is the rotational locomotion platform shown in figure 18 (a) and (c). In order to be able to test the prototype
Figure 18: a) Monolithic rotational stick-slip platform, functioning principle, b) monolithic $X, Y, \theta_z$ stick-slip locomotion platform, c) fabricated prototype of the rotational platform ($10 \times 10 \times 0.5 \text{ mm}^3$) d) fabricated prototype of the $X, Y, \theta_z$ platform ($10 \times 10 \times 0.5 \text{ mm}^3$)

Figure 19: Results obtained with the $X, Y, \theta_z$ stick-slip locomotion platform of figure 18 (b) and (d)

without the obstruction of the wires, the PZT element is mounted upside down with a small plate ($16 \times 16 \text{ cm}^2$) laid on top of the feet. The asymmetrical vibration of the feet made the plate turn at a maximum velocity of 0.25 rpm. If each pair of half circles is polarized in anti-parallel sense, the platform can be actuated with just two wires. In a second prototype, the electrodes of the push-pull subactuators have been rearranged on the border of the PZT-plate, resulting in two degrees of freedom for every sub-actuator and three degrees of freedom ($XY\theta_z$) for the locomotion platform (see figure 18 (b) and (d)).

This $XY\theta_z$ locomotion platform has been tested in the same way as the rotational platform. Figure 19 shows the measured velocities in function of the driving voltage and frequency. The graph clearly illustrates the high bandwidth of the locomotion platform (driving frequencies up to 10 kHz).
Figure 20: a) Principle of the tool positioner b) fabricated prototype of the tool positioner

### Table 2: Measurements on the rotational actuator

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Peak Current [mA]</th>
<th>Torque [µNm]</th>
<th>Speed [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 Vpp</td>
<td>60</td>
<td>38.5</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>34.8</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>24.7</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>18.5</td>
<td>0.36</td>
</tr>
<tr>
<td>200 Vpp</td>
<td>70</td>
<td>67.9</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>49.8</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>20.9</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>16.8</td>
<td>0.55</td>
</tr>
</tbody>
</table>

**6.2.3 Handling modules**

The robotic agents have to be equipped with tools such as grippers, AFM tips and micro-syringes. Additional actuators are therefore required. A positioner for the tools has been developed, which can be attached to the individual agents and which can carry the necessary tools. It is a stick-slip rotational actuator. Its main characteristic is that all stick-slip elements (piezo, guides and rotor) are in the same plane, making the actuator only 500 µm thick for a diameter of 8mm.

The actuating part in the center is cut from a PZT sheet. A ring with a V-profile is fixed on the the PZT part. The outer mobile part (rotor) is cut from a steel sheet and has polished cylindrical pins fixed to it, guaranteeing for a smooth motion of the rotor. In order to generate the desired motion, the PZT part is cut and the electrodes are patterned. Two actives zones having a circular shape induce the rotational movement, with the surrounding material.
being passive.

To guarantee the contact of the guide and to increase the contact force, which directly increases the thrust force in stick-slip systems, a spring load system has been added. This system is in the same plane as well in order to keep the thickness as small as possible.

Tests have been carried out to measure the characteristics of the tool positioner. The force of the tool positioner has been measured with a precision balance having an accuracy of 1mg. The table 2 shows, that the peak current is the limitation for the actuator, since it directly affects the slew-rate of the sawtooth and therefore the backlash. We can see that this factor is directly proportional to the speed and to the torque.

7 Conclusion

In this paper, an overview was given on recent developments at LSRO in the field of piezoelectric manipulators, focusing particularly on systems which can potentially be used in microbiology applications. The X-Y Stage with the MPA concept presents interesting features such as simplicity and compactness allowing to realize a complete AFM with a thickness of 2mm. However, fragility and low natural off-plane frequency still limit the field of applications. The bimorph-based stages are less fragile but require more effort in assembly and have a longer range.

Several systems based on piezoelectric stepping motors (stick-slip motors) were shown as well. The simple principle allows for a compact design which is not possible with traditional motorized stages or micromanipulators. At the same time superior performances are possible, as the piezoelectric elements allow for nanometric resolutions, making the proposed tools interesting as well for applications in SPM or SEM setups. With the proposed locomotion platforms and tool positioners it is possible to conceive simple robotic agents, which will form a micromanipulation setup for semiautonomous and autonomous handling of small objects, in particular cell samples.

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