*Proc. of 9th Int. Precision Engineering Seminar & 4th Int. Conf. on Ultraprecision in Manufacturing Engineering*, Braunschweig, Germany, 1997.

# Monolithic Piezoceramic Flexible Structures for Micromanipulation

J.-M. Breguet, S. Henein, R. Mericio, R. Clavel
Institut de microtechnique (IMT), Swiss Federal Institute of Technology (EPFL),
CH-1015 Lausanne.

**Abstract**

This paper presents several flexible structures cut directly into piezoelectric ceramics. Some parts of these structures are active while other play the role of joints or levers. With this innovative technology, the displacement of the piezos has been amplified by a ratio greater than 50 to 1. The actuating principle is discussed and the following three prototypes are presented. A micro-gripper with an integrated force sensor and a X-Y stage have been tested and characterized. A micro-robot actuated by Stick & Slip has also been developed taking advantage of this new technology.
We believe that this new approach is of promise in the micro-manipulation and Scanning Probe Microscopy (SPM) fields.

## I. Introduction

A well known limitation of the piezoelectric actuators is their limited displacement compared to their dimensions. Typically, a PZT piezoceramic has a relative deformation ≤ 0.015% for an applied voltage of 100 V.
Several ways of amplifying the movement are possible. A multilayer piezo actuator, composed of a stack of several thin piezo elements, allows a relative deformation up to 0.15% at 100 V, while a bimorph actuator presents a maximum deformation of 0.25%. Nevertheless its rigidity is much lower than the one of a multilayer actuator [1].
The piezo movements can also be amplified by lever mechanisms [2]. Unlike usual approaches, with our technology, the piezo actuators, the joints and the lever mechanism are cut directly into the same piece of PZT ceramics, thus avoiding further delicate and expensive assembly process. The tested prototypes have a measured amplification ratio (defined in paragraph III) of 0.25%, the same as the bimorph. With an optimized design, this ratio will be improved to 0.35% and even more.
A quite different way to overcome the piezos' small movements is to use the addition of many small displacements, allowing stepping motion and virtually unlimited strokes. Inch worm or Stick & Slip actuators rely on this principle [3]. A 3-degrees-of-freedom micro-robot using Stick & Slip actuators will also be briefly described in this paper.

## II. Principle

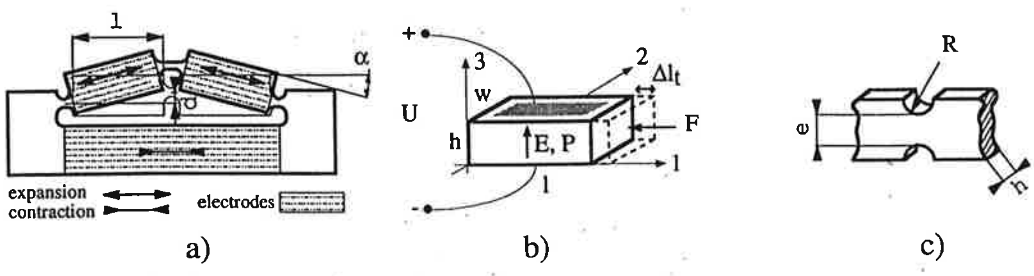



Figure 1 a) Principle of the Monolithic piezoceramic flexible structure, b) transversal actuator and c) notch hinge.

We propose to combine the actuators, the joints (also called notch hinges) and the lever mechanisms in a single plate of piezoceramic (PZT) polarized through its thickness. The ceramic, typically 1 mm thick, is cut by laser. Electrodes are designed in order to render active only the parts of the piezo which are underneath them. In this manner we obtain transversal piezo actuators, whose movements can be chosen arbitrarily in any direction. The amplifying effect is given by a small misalignment $d$ of the central joint. Contracting one actuator and expanding the other the mobile part rotates by an angle $\alpha$ (figure 1). This rotation can be transformed into a translation using a lever.

## III. Calculation

The deformation of a transversal actuator is given by:

$$\Delta l_t = d_{31} \cdot U \cdot \frac{l}{h} - \frac{F}{C_{Et}} \qquad \text{(eq. 1)}$$

where $d_{31}$ is the piezoelectric charge constant, $U$ the voltage, $l$ the length, $h$ the thickness, $F$ an external force and $C_{Et}$ the actuator rigidity. Supposing that $\Delta l_t << l$ and after linearization, the rotation is given by:

$$\alpha \cong \frac{2 \cdot \Delta l_t}{d} \qquad \text{(eq. 2)}$$

The angle $\alpha$ is limited by the maximum strain in the notch [4]:

$$\alpha_{max} = \frac{3 \cdot \pi}{16} \cdot \frac{\sigma_{max}}{E_{11}} \cdot \sqrt{\frac{R}{e}} \qquad \text{(eq. 3)}$$

where $R$ is the radius of the notch and $e$ the thickness of the neck (figure 1).
Assuming that the force $F$ in equation 1 is negligible (we will see in paragraph V that this is not the case), we can calculate the length $l_{max}$ which gives the maximum rotation:

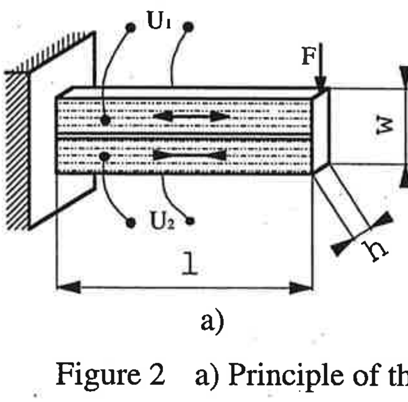
$$l_{max} = \frac{3 \cdot \pi}{32} \cdot \frac{\sigma_{max}}{E_{11} \cdot d_{31} \cdot U} \cdot \sqrt{\frac{R}{e}} \cdot b \cdot d \qquad \text{(eq. 4)}$$

We define the maximum amplification ratio as:

$$G_{max} = \frac{\alpha \cdot l}{\Delta l} = \frac{3 \cdot \pi}{16} \cdot \frac{\sigma_{max}}{E_{11} \cdot d_{31} \cdot U} \cdot \sqrt{\frac{R}{e}} \cdot b \qquad \text{(eq. 5)}$$

We applied equations 1 to 5 to design the prototypes presented in paragraph V.

## IV. Force sensor



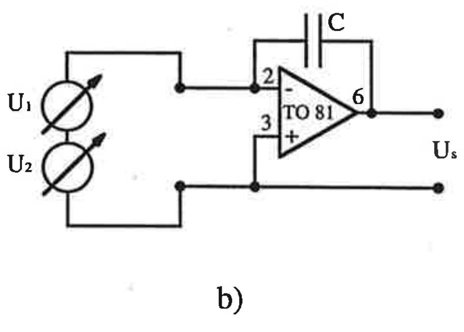




Figure 2 a) Principle of the force sensor and b) electronic circuit.

A force $F$ applied on the free end of a cantilever (figure 2 a) causes bending and therefore a tensile force in the cantilever upper part and a compressive force in the lower one. Thus a positive, respectively negative charge is generated on the electrodes. The charge is generated only when there is a change in the applied force. For static loads it will leak away across the input resistance of the measuring device [1]. The very high input impedance of the charge amplifier shown in figure 2 b) allows a time constant of several seconds.
The sensitivity of this force sensor, including the charge amplifier is given by:

$$s = \frac{U_s}{F} = \frac{3}{4} \cdot d_{31} \cdot \frac{1}{C} \cdot \frac{l^2}{h \cdot w} \quad \text{V/N} \qquad \text{(eq. 6)}$$

Experiments confirm the good correlation with equation 6 (figure 3).

## V. Description of the prototypes

Several prototypes have been designed which rely on the principle described above. The first one is a micro-gripper (figure 4). The thick finger is fixed while the thin one moves to grips (it could include a force sensor as described in paragraph IV). The kinematics of the gripper multiplies the angular movement of its fingers making it 4 times $\alpha$. Furthermore, the 14 mm long fingers act as levers, amplifying the movement of the gripper's tips. Assuming that the angular stiffness of the notch hinges is null, the movement of the gripper's tips would theoretically be $\pm$ 69 µm for a $\pm$ 150 V voltage. But the measured movement is only $\pm$ 18 µm (figure 5).

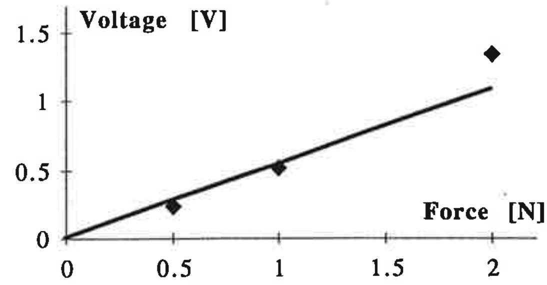
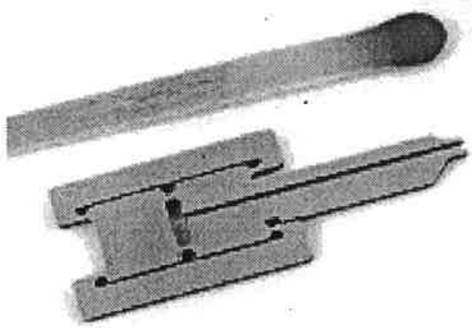
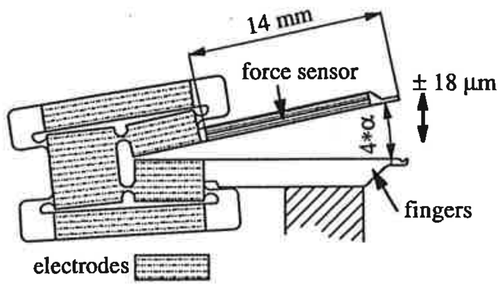



Figure 3 Force sensor:
Theoretical sensitivity: $s$ = 0.54 V/N.
Measured sensitivity: $s$ = 0.56 V/N.
$l$ = 16 mm, $h$ = 1 mm, $w$ = 2 mm, $C$ = 68 nF.



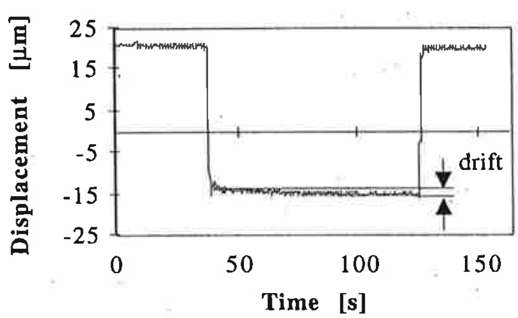


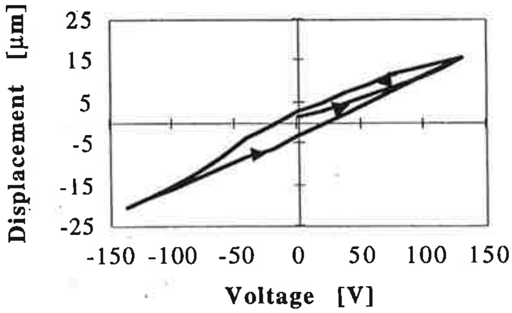

a) b)

Figure 4 Micro-gripper a) micro-gripper's picture
b) open position (exaggerated movement)

This large difference can be explain by the fact that the angular stiffness of the notch hinges cannot be neglected: it opposes bending and tensile stresses to the piezo's movements which reduce its actual deformation. As the misalignment $d$ increases, these stresses decrease, but $\alpha$ decreases as well. Therefore an optimum exist for $d$ which induces the greater displacement for a given voltage on the piezos. Taking these stresses into account, a model has been developed (not described in this paper). The theoretical values obtained are within 5% of the measured ones. The model allows to find that the optimum $d$ is 0.65 mm which would induce a displacement of $\pm$ 23 µm (instead of $\pm$ 18 µm obtained with $d$ = 0.23 mm).

Figure 5 shows the drift and the hysteresis, two typical feature of piezoelectric actuators. Both

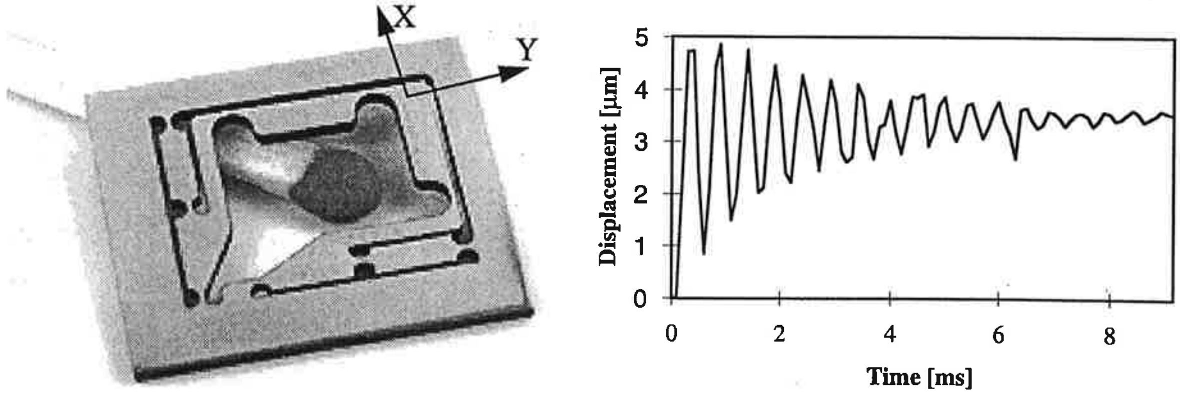



a) b)

Figure 5 Micro-gripper: a) stepping response, settling time 15 ms (the drift is visible),
b) hysteresis.

effects can be almost eliminated using a charge amplifier instead of a voltage amplifier [1].




a) b)

Figure 6 X-Y stage: a) stage's picture, b) step response, settling time 6 ms.

The second prototype is a X-Y stage with ± 3 µm strokes (figure 6). The design of a X-Y-Z stage is being considered. The Z-axis would rely on the same amplifying principe. We will also consider the possibility of integrating position sensors, based on the principle of the force sensors described above.
The third prototype is a Stick & Slip actuator. The use of monolithic piezo technology simplifies remarkably the construction of this type of actuators [3]. For example, we designed a 3-DOF micro-robot with only 6 mechanical parts.

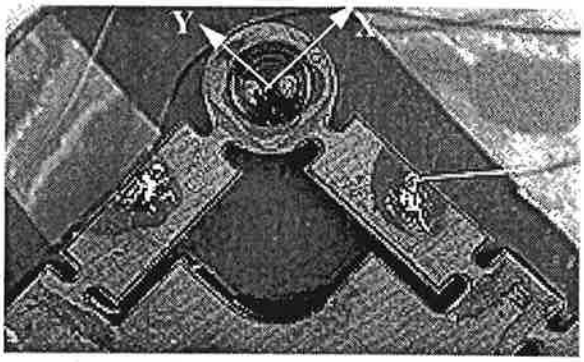



Figure 7 Detail of the 3-DOF micro-robot.

## VI. Conclusion

We are still at an early stage of development of the monolithic piezoceramic flexible structures but we believe in the great potential of this innovative technology. This paper describes interesting means of amplifying the piezos' movements and shows prototypes which prove the realism of this new approach. The theoretical model predicts larger strokes for optimized designs and the photolithography and MEMs technologies will allow further miniaturization.


## Acknowledgment

The authors are grateful to Dr. T. Siedler for the laser cut of the prototypes.


## References


[1] Philips, *Piezoelectric Ceramics Properties and Applications*. 1991.

[2] S. T. Smith and D. G. Chetwynd, *Foundations of Ultraprecision Mechanism Design*. Developements in Nanotechnology, ed. D. K. Bowen. Vol. 2. 1994, Warwick, UK: Gordon and Breach Science.

[3] J.-M. Breguet, E. Pernette and R. Clavel. *Stick and slip actuators and parallel architectures dedicated to microrobotics*. presented at the conf. *Microrobotics: Components and Applications, SPIE's Photonics East*. 1996.Volume 2906, pp13-24, 21-22 November, Boston.

[4] J.-M. Paros and L. Weibord, *How to design flexure hinges*, in *Machine Design*. 1965, pp 151-156.