Development of a XY Piezoelectric Nanopositioner

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Abstract. *Piezoelectric actuators are applied as force, pressure and acceleration sensors and most recently to the design of micro and nanopositioners. In this project three piezo-nanopositioner XY were developed which consist essentially of piezoelectric ceramics bonded to a compliant mechanism that can amplify the ceramic displacement. In a compliant mechanism the movement is due to the flexibility of the structure instead of the presence of joints and pins. As design performance, it is desired to obtain the maximum possible displacement with a piezoelectric ceramic with a minimum crosstalk between displacements X and Y. To evaluate these design characteristics, FEM models of the three actuators were built and simulated using the finite element commercial software ANSYS. With the results of maximum displacement and the crosstak levels between X and Y displacements it is possible to evaluate the quality of the nanopositioner designed. Prototypes of XY nanopositioners were manufactured in micromachining laboratory of Sincroton Light National Laboratory (LNLS - Campinas) through the lithography technique based on chemical corrosion of 60 μm and 100 μm thickness copper plates. As future work, displacements and the crosstalk levels generated by nanopositioners should be measured through laser interferometry.*

Keywords. *nanopositioners, piezoelectric actuators, FEM modeling, MEMS, compliant mechanisms, lithography.*

1. Introduction

Piezoelectric materials are usually applied to build force, acceleration and pressure sensors, actuators, devices that generate acoustic waves (such as loud speakers, ultrasonic transducers), and more recently to build micro and nanopositioning systems. Mechanisms that require nano or micrometric displacements are applied to precision mechanics devices such as mechanism of a hard disk, microsurgery equipment, electronic microscopy, etc (Barillot et al., 2000) and also to position mirrors or samples in laser interferometry devices (Barillot et al., 2001).

A comprehensive discussion on the design of compliant mechanisms and nanopositioners has been made along the last years (Howell, 2000); (Smith, Chetwynd, 1992). In several works there is a discussion about the characterization of piezo-nanopositioners through FEM simulation (Tseng, 1999); (Kim, Kim, 2001); (Barillot et al., 2001). The modeling and the design of a compliant mechanism used in a piezo-micropositioner are discussed in (Barillot et al., 2001). This mechanism amplifies the ceramic displacements through levers. The design of a piezoelectric actuator applied to control the inclination of a laser interferometry mirror is presented in the same work. The modeling and the design of XY piezo-positioners through FEM are frequently nowadays (Moaveni, 1999); (Tseng, Chien, 1999). There are sophisticated examples of piezo actuators in the literature, such as the piezo-micropositioner (Tseng, 1999); (Tseng, Chien, 1999) that has displacement amplification levers and four pizoelectric ceramics responsible for generating displacements. Relatively simple geometry XY piezo-actuators also are treated in the literature (Kim, Kim, 2001). Besides being simpler they are easier to manufacture and they can help the understanding and the study of more complex mechanisms.

To transmit nanometric displacements these actuators can not be implemented using the traditional mechanism technology, based on joints, pins and guides. Gaps on traditional mechanisms joints makes practically impossible to achieve micro or nanometric resolution (Smith, Chetwynd, 1992).

The appropriate technology to design these actuators is based on compliant mechanisms. These are mechanisms where the action is given by the structural flexibility and not by the presence of joints and pins (Howell, 2000); (Smith, Chetwynd, 1992). They are made in a single part and they can also amplify and change the direction of ceramic displacements. For being made in a single part compliant mechanisms are easier to assembly and also arises the possibility of microfabrication (MEMS), being that the reason why the compliant mechanisms are very used in ultraprecision mechanics (Smith, Chetwynd, 1992).

In spite of being essential in the nanopositioners design, compliant mechanisms produces an undesired effect, which is the crosstalk between X and Y displacements (Tseng, 1999); (Tseng, Chien, 1999), that is, the displacement in a direction results in a spurious displacement in the perpendicular direction. This means that special cares to solve this problem should be taken in the design of ultraprecision nanopositioners.

Thus, the goal of this work was to design three different XY piezoelectric nanopositioners models and evaluate their performance by using FEM simulation. The following actuators were build to achieve the maximum displacement in X and Y direction with a minimum crosstalk between the X and Y directions. They were modeled and simulated by using the finite element method, considering a static analysis to verify the maximum displacement, and the crosstalk level between X and Y directions. After simulated and evaluated, some prototypes were manufactured through the lithography technique using the micromachining laboratory of Sincroton Light National Laboratory (LNLS - Campinas).

This paper is organized as follows: The precision XY micropositioner concepts, as well as suggested models of precision nanopositioner are introduced on the second section. On the third section, the FEM modeling of piezo-nanopositoners is described. On fourth section, simulation results are discussed. The manufacturing by litography and chemical corrosion technique are treated on fifth section. Finally, in sixth section, the conclusion and future work suggestions are given.

2. The Design of XY Nanopositioners

Several special cares should be taken on the design of XY precision actuators. To achieve nanometric resolution displacements, the designed mechanism can not have joints and pins, because any small gap in the mechanism would make the actuator totally inaccurate. Thus, these mechanisms were designed using compliant mechanisms.

The main problem in this kind of mechanism is the crosstalk between X and Y directions, which generates spurious displacements, once the deformation of part of the structure implies in the deformation of the entire structure. If there is the intention of a displacement in the Y direction, an undesired displacement appears in the X direction.

The problem of spurious displacements should be contoured with special care in the design such as, for example, the inclusion of notchs (flexural hinges) that act like springs, giving more flexibility to the compliant mechanism critical points (Howell, 2000); (Smith, Chetwynd, 1992); (Kim, Kim, 2001). Actually these flexural hinges are finer parts of the structure, making more flexible that region.

Based on this idea (Howell, 2000); (Smith, Chetwynd, 1992); (Tseng, 1999); (Silva et al., 2000), three piezo-nanopositioners were designed. In all models the strain generation is obtained by applying an electric voltage to a piezoelectric ceramic. The piezoelectric ceramic deformation will make the compliant mechanism to deform generating the desired displacement. Following each designed model is described:

Model 1: It consists of two "Moonie" (Silva et al., 2000) actuators coupled by two bars. In this mechanism four flexural hinges were placed in the bars that link the “Moonies” with the purpose of decreasing the crosstalk between displacements X and Y.

Model 2: It is a little more sophisticated than the previous model because it has a lever system that amplifies the displacement generated by the "Moonie" actuators. Amplification of the generated displacement is an interesting design characteristic, because piezoelectric ceramic displacement has nanometric order (Smith, Chetwynd, 1992); (Barillot et al., 2001). In this mechanism six flexural hinges were placed with the purpose of decreasing the crosstalk between X and Y displacements.

Model 3: this model was based on references (Tseng, 1999); (Tseng, Chien, 1999). It has four piezoelectric ceramics coupled directly to the compliant mechanism. It also has an amplification system based on levers and a crosstalk decrease system based on finer bars in critical points of the structure.

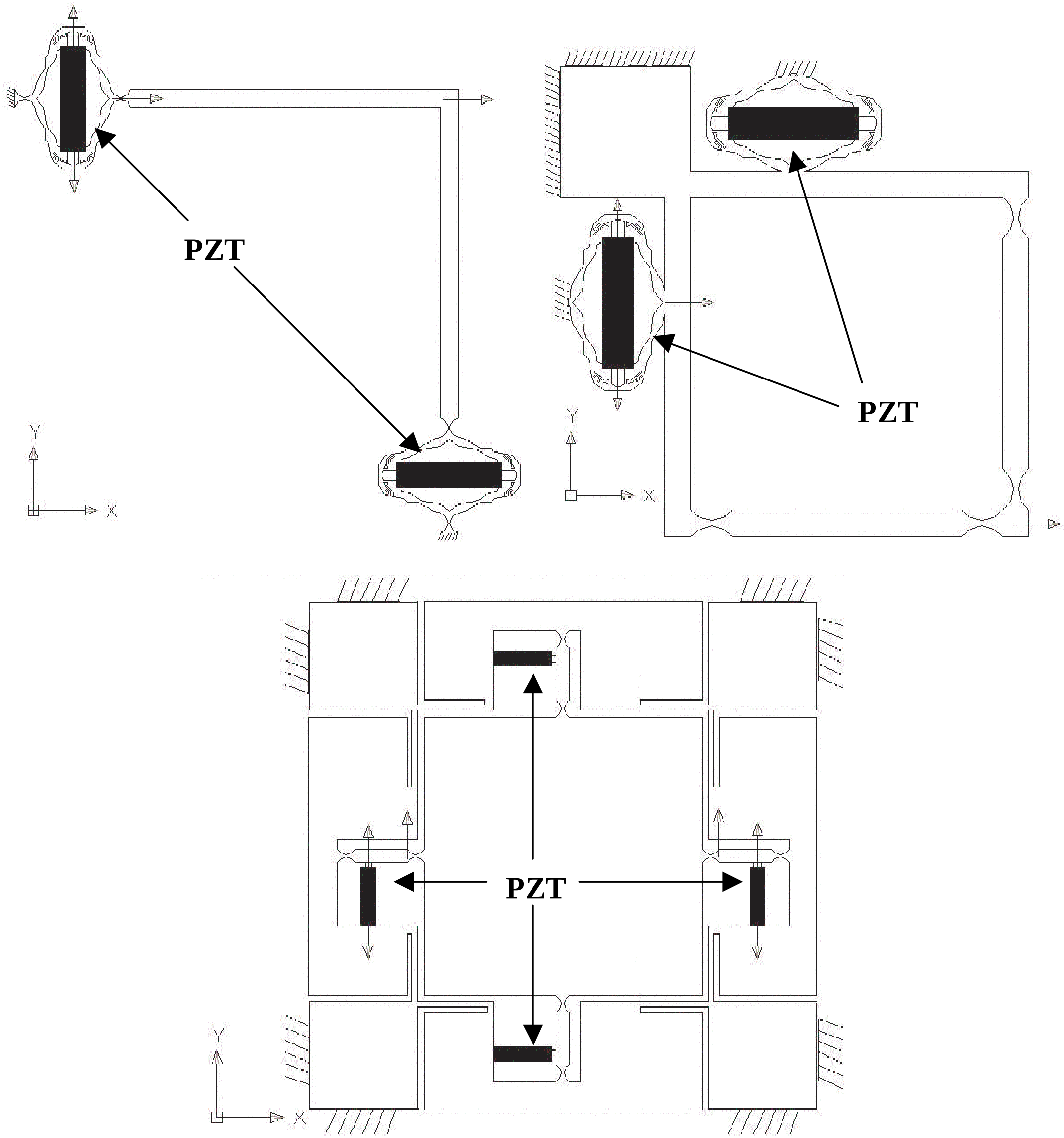

Figure 1. Models 1, 2 and 3 with arrows indicating the direction of the displacements in the structure.

A quantitative measure of the crosstalk levels between X and Y displacements can be given in therms of percentage by the following expression:

$$A_{xy} = \frac{\Delta x}{\Delta y_s} \tag{1}$$

where Δx is the desired displacement in the X direction and Δy_s is the spurious displacement found in Y direction when attempt to displace in X. The crosstalk level between the Y and X displacements can be defined in the same way:

$$A_{yx} = \frac{\Delta y}{\Delta x_s} \tag{2}$$

where Δy is the desired displacement in the Y direction and Δx_s is the spurious displacement found in X direction when attempt to displace in Y. Thus, it is important to increase or have a big value of A_{xy} and A_{yx}.

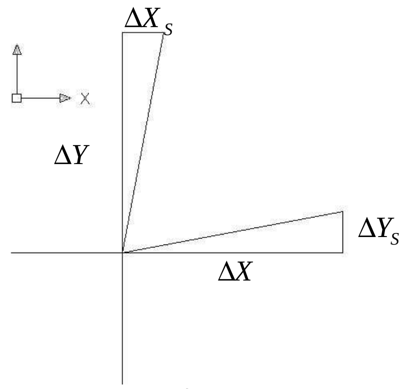

Figure 2. Spurious displacements generated in the attempt of dislocating in a direction.

3. The FEM Modeling

When modeling the electromechanical behavior of the piezoelectric nanopositioners, the following constitutive equations were used (Tseng, 1999); (Nader, 2002); (Naillon et al., 1983):

$$\{\mathbf{T}\} = \left[c^E\right]\{\mathbf{S}\} - [e]\{\mathbf{E}\} \tag{3}$$

$$\{\mathbf{D}\} = [e]^T\{\mathbf{S}\} + [\varepsilon^S]\{\mathbf{E}\} \tag{4}$$

where $\{\mathbf{T}\}$ is the mechanical stress vector, $\{\mathbf{S}\}$ is the strain vector, $\{\mathbf{E}\}$ is the electric field vector, $\{\mathbf{D}\}$ is the electric displacement vector, $\left[c^E\right]$ is the material elastic stiffness matrix for a constant electric field, [e] is the piezoelectric matrix and $[\varepsilon^S]$ is the material permitivity matrix for a constant deformation. These equations together with the balance equation allow us to apply FEM theory to model piezoelectric materials. The piezoelectric nanopositioners designed where modeled using the finite element method. When modeling the piezoelectric static behavior the FEM matrix equation is simplified as below (Naillon et al., 1983):

$$\begin{bmatrix} K_{uu} & K_{u\phi} \\ K_{u\phi}^{\ T} & K_{\phi\phi} \end{bmatrix} \begin{Bmatrix} U \\ \phi \end{Bmatrix} = \begin{Bmatrix} F \\ Q \end{Bmatrix} \tag{5}$$

where K_{uu} is the mechanical stiffness matrix, $K_{u\phi}$ is the piezoelectric coupling matrix and $K_{\phi\phi}$ is the electric permitivity matrix. The terms U and ϕ are the nodal displacement vector and nodal electric potential vector, respectively. The mechanical and the electrical loads are expressed through terms of F and Q, respectively.

In the FEM analysis, the ANSYS software was used. For the 2-D finite element model of nanopositioners PLANE-42 with two degrees of freedom (X and Y) were applied to model the elastic structure and PLANE-13 with three degrees of freedom (X, Y and VOLT) were applied to model the piezoelectric materials (Moaveni, 1999); (Ostergaard, Pawlak, 2000). For all modeled structures the plane stress assumption was adopted due to the fact the considered mechanisms are essentially plane structures (Ostergaard, Pawlak, 2000). In these models two different materials were considered, copper and piezoelectric ceramic. The properties of used materials are described in the Appendix section.

A constant electrical potential was applied to the piezoelectric ceramics. As boundary conditions some nodes corresponding to the fixed parts of the structures (as shown in the figure 1), were fixed in X and Y directions. The finite element mesh of models are shown below.

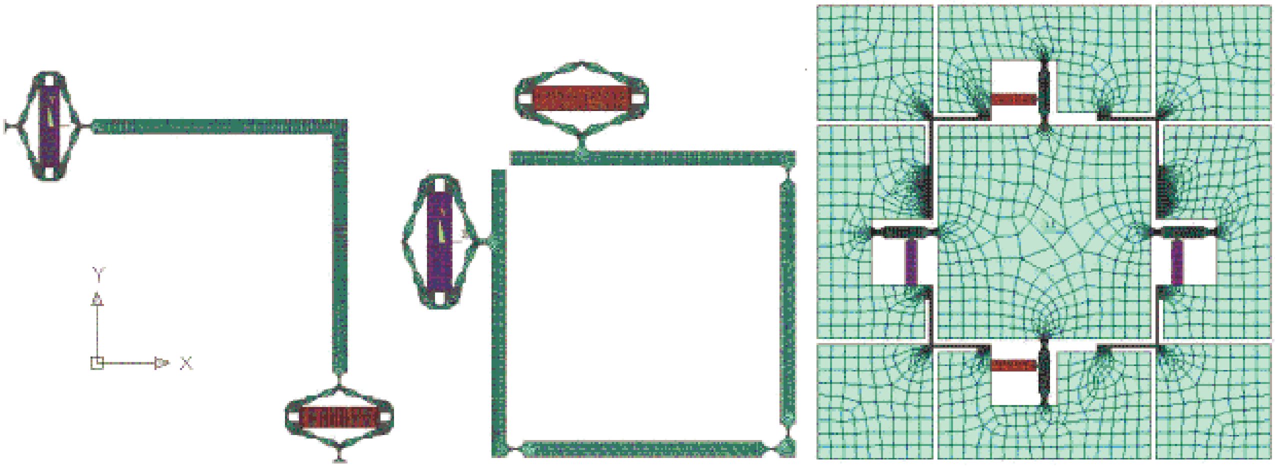

Figure 3. Models 1, 2 and 3 finite element mesh, respectively.

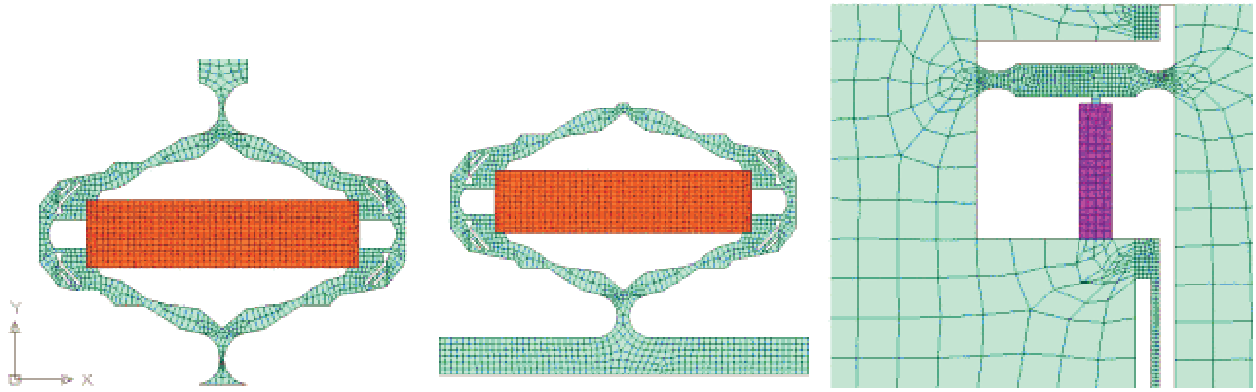

Figure 4. Detail of refinement of finite element mesh of models 1, 2 and 3, respectively.

The first finite element mesh model has 3983 elements. The second model has 5771 elements and the third model has 5916 elements. Due to third model complexity, different sizes of elements were used to model it. More geometric detailed parts of this structure were modeled with a finer element mesh.

4. Results

Through the simulations obtained with FEM, it was possible to choose the best solution for the XY piezo-nanopositioner problem. The simulations allowed us to analyze displacements generated by several mechanisms and the crosstalk level between X and Y displacements.

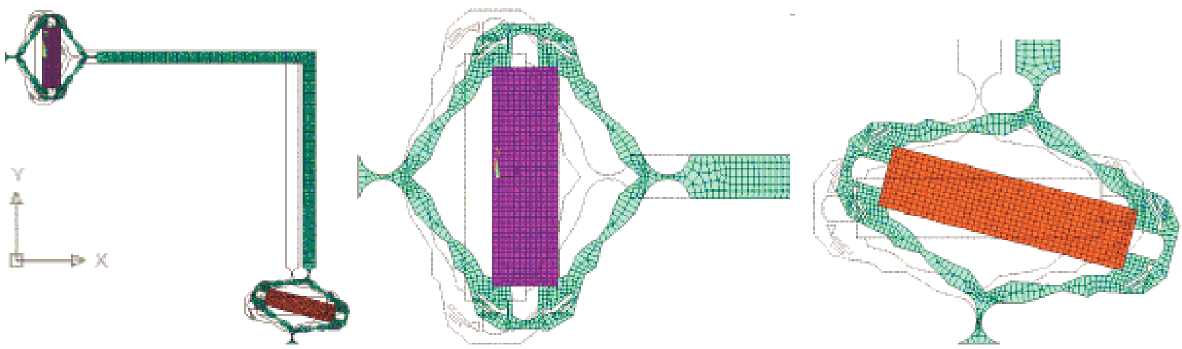

Figure 5. Deformed configuration of model 1.

For each nanopositioner model previously suggested, an electric potential of 100 V was applied to the piezoceramic responsible for the Y displacement while the ceramic responsible for the X displacement was grounded. Thus, it is possible to obtain a displacement in the Y direction and the undesired displacement in the X direction. The next step was to apply an electric potential of 100 V to the piezoceramic responsible for the X displacement while grounding the piezoceramic responsible for the Y displacement. Thus, it is possible to measure the displacement generated in the X direction and the undesired Y displacement.

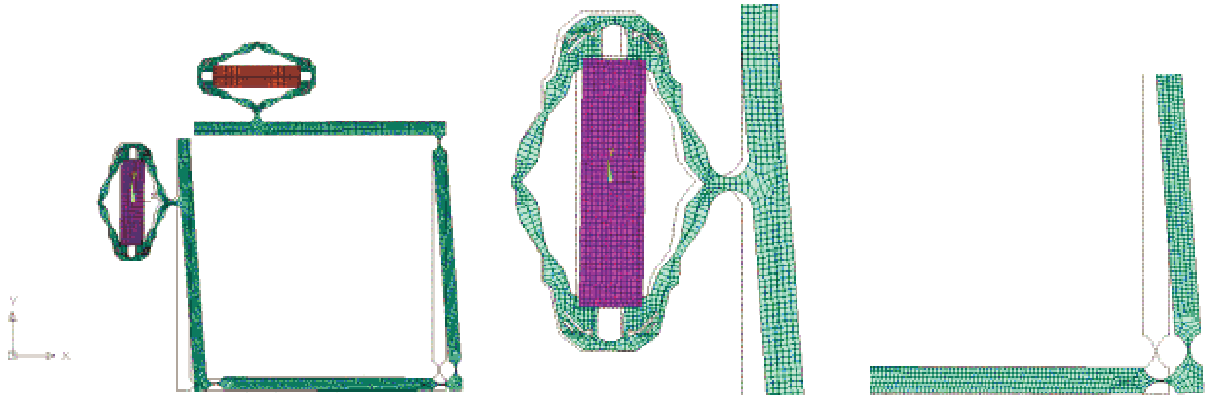

Figure 6. Deformed configuration of model 2.

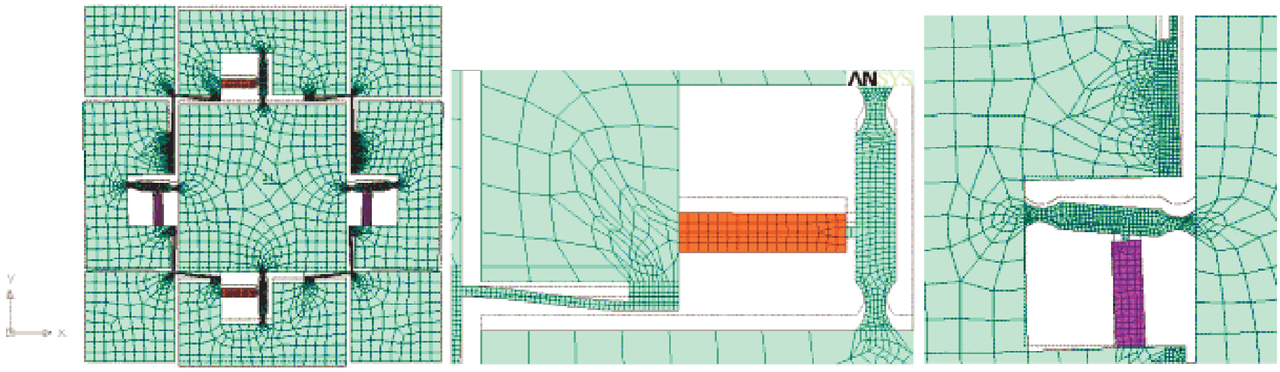

Figure 7. Deformed configuration of model 3.

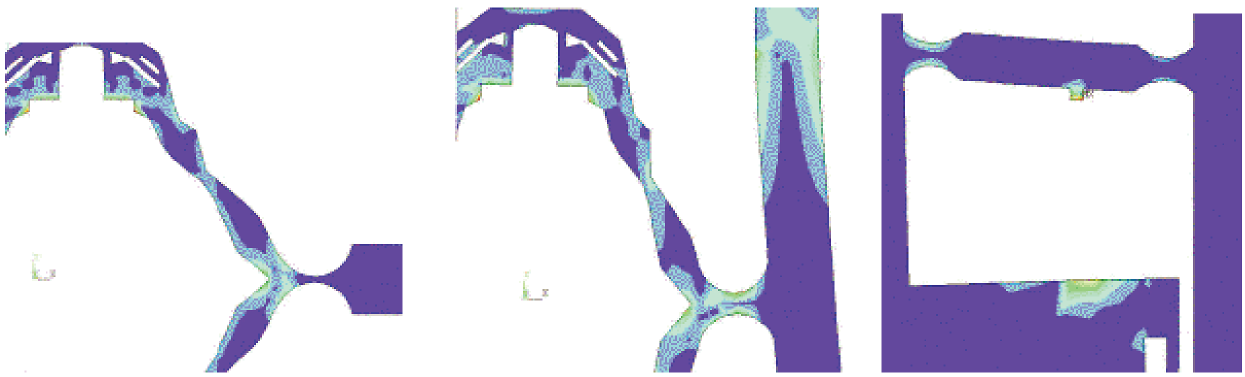

Figure 8. Von-Mises stress concentrations in models 1, 2 and 3 respectively.

In figure 8 the Von-Mises stress concentrations in nanopositioner can be observed. Regions with a direct contact with the piezoceramic and regions where a larger flexibility of the structure is needed have larger Von-Mises stress concentration.

Table 1. Simulations results using the models above:

Simulated structure	Voltage in the X Ceramic [V]	Voltage in the Y Ceramic [V]	X Displacement [nm]	Y Displacement [nm]	A_{xy}	A_{yx}
Model 1	0	100	0.003	58	-	19300
Model 1	100	0	58	0.003	19300	-
Model 2	0	100	10	210	-	21
Model 2	100	0	210	10	21	-
Model 3	0	100	0.01	40	-	4000
Model 3	100	0	40	0.01	4000	-

Looking at this table, it is possible to predict the manufactured nanopositioners behavior.

The model 1 for being the simplest, has low values of displacements. It does not have an amplification mechanism, however it did not introduce a large value of crosstalk between X and Y displacements. Its geometric simplicity makes the mechanism the easiest one to manufacture.

The second model amplifies 4 times the piezoelectric ceramic displacement. This amplification has a cost, it increases the undesired displacement in the perpendicular direction. The increase of the geometry complexity will also increase the difficulty of manufacturing process for this model.

Even though the third model has an amplification mechanism, it generated smaller displacements than the previous model. It happened because the previous models used the "Moonie" (figure 1) which is an optimized compliant mechanism that changes the direction and amplifies the piezoelectric ceramic displacements (Silva et al., 2000). The geometric complexity of the mechanism implied in a low crosstalk between X and Y displacements, but it also causes a difficulty to manufacture this mechanism. Other disavantage is that model 3 operates with four piezoelectric ceramics. The four ceramic operation allows a θ displacement (rotation) which is not possible in the other mechanisms.

5. Manufacturing

The proposed models above were manufactured in the micromachining laboratory of Sincroton Light National Laboratory (LNLS - Campinas). The prototypes were made using lithography techniques which is a low cost manufacturing technique to produce the simulated models. To apply this technique it is necessary to export the ANSYS model to a CAD software. Some fittings in the lines are necessary to achieve a 150 μm resolution impression. The masks were printed by a company specialized in printing high-resolution masks (as shown in figure 9). The LNLS equipment imposed that these masks should have a 50 mm maximum size. With the masks done, the next step is to sensitize the 60 and 100 μm thickness copper plates to be corroded. This is made using ultraviolet light and a photoresist, which protects against corrosion the material desired parts. Next step is the material corrosion. This was made in a solution containing 250 g of ferric percloret and 500 g of water, this solution is heated to 60° C.

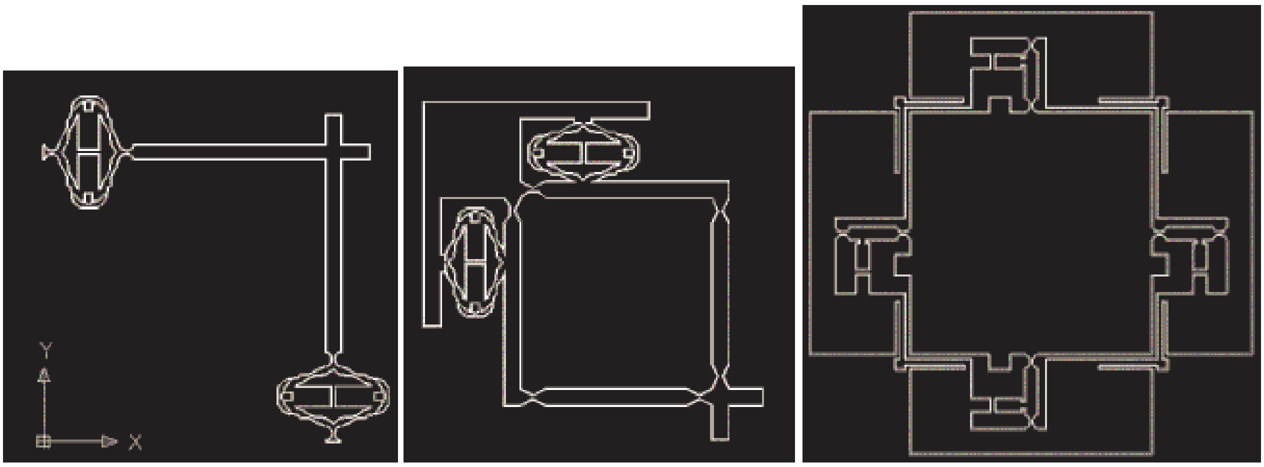

Figure 9. The three printed masks. The white parts will corroded.

It is observed on the printed masks above that small brims were introduced to the designed structures. These brims will be useful on the displacement measurement through laser interferometry. After manufactured these brims should be carefully folded or lifted (the brims must be perpendicular to the actuators plane). After lifting them, it is necessary to bond a little mirror on these brims to measure the displacements through laser interferometry

The corrosion is monitored in time intervals of 3 minutes (for 60 µm thickness plates) and 5 minutes (for 100 µm thickness plates). This control was done through a microscope and it was very important to evaluate how long the structures should be exposed to corrosion. The first attempts of manufacturing were not very successful. The masks were exposed to corrosion a larger time than the necessary and this broke the structures in some critical points (smaller thickness points). As predicted in the project, the sophisticated models were more difficult to manufacture.

The third model has lots of critical points (many fine line, measuring 150 µm) due mostly to the levers system that amplify the movement and due to the system of fine bars that act like springs, decreasing the crosstalk between the X and Y displacements.

The first and the second models were easier to manufacture, they have a smaller quantity of fine lines (150 µm lines) which implies less problems during the corrosion. Besides the flexural hinges (lines with 150 µm), some parts of the Moonie structure were also a critical point to the corrosion. Since it has six flexural hinges the second model corrosion process was a little more laborious than the first model corrosion process. For having only four flexural hinges, the first model, was the easiest to manufacture. It is possible to observe the corrosion critical points of prototypes in figure 10. Following the pictures of manufactured prototypes:

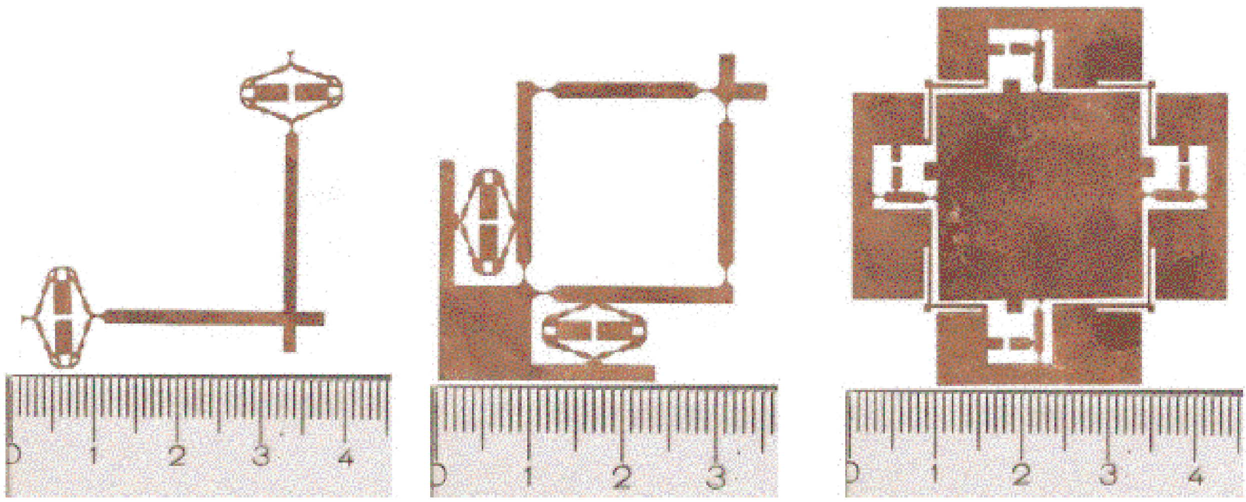

Figure 10. Pictures of the manufactured actuators. Models 1, 2 and 3, respectively.

In all models, displacements generated by the piezoelectric ceramic, are transmitted by shear to the manufactured compliant mechanism. The ceramics should be bonded to the manufactured structure with a silver ink (or another conducting material). Thus, it is possible to apply a voltage to the piezoelectric ceramic and use as reference voltage (ground) the compliant mechanism conductive base.

To decrease the displacement generated in the Z direction (due to the low thickness of the structure), it is possible to bond structures, forming a stack of layers that increase the mechanism thickness. The thickness increase, decreases not only the undesired displacements in Z direction but also the buckling problem.

6. Conclusion

The design, simulation and the manufacturing of XY piezo-nanopositioners were introduced in this paper. The three designed models have special characteristics that aim the decrease of the crosstalk level between the displacements X and Y and to maximize the displacement in the desired direction. The crosstalk levels and maximum displacement were obtained through FEM simulations.

The structure manufacturing using the lithography and corrosion technique was a very interesting part of the work. Its low cost and fast execution time (in eight hours is possible to do about 12 prototypes) allows us to construct fast prototypes aiming preliminary tests and also allows its application to the teaching of piezoelectric actuator project, since students can learn to design, to simulate these mechanisms and can also make prototypes for testing their projected models. As future work, these nanopositioners will be measured by using a laser interferometer and they will be applied to assist positioning of samples for laser interferometer measuring.

7. Acknowledgements

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9. Appendix

On the nanopositioners modeling, the following properties were used for piezoelectric ceramic and copper plates.

Compliant Mechanisms (Copper):

Density: $\rho = 2000$ kg/m³
Young´s modulus: E = 119 GPa
Poisson´s ratio: $\nu = 0.33$

Piezoelectric Ceramics:

Density: $\rho = 7800$ kg/m³

Electric Permitivity:

$$\varepsilon_x = 1.5293 \cdot 10^{-8}$$
$$\varepsilon_y = 1.379 \cdot 10^{-8} \qquad \frac{F}{m}$$
$$\varepsilon_z = 1.5293 \cdot 10^{-8}$$

Elastic Stiffness Matrix:

$$[\mathbf{c}] = \begin{bmatrix} 1,21\cdot10^{11} & 7,52\cdot10^{10} & 7,54\cdot10^{10} & 0 & 0 & 0 \\ 7,52\cdot10^{10} & 1,11\cdot10^{11} & 7,52\cdot10^{10} & 0 & 0 & 0 \\ 7,54\cdot10^{10} & 7,52\cdot10^{10} & 1,21\cdot10^{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2,11\cdot10^{10} & 0 & 0 \\ 0 & 0 & 0 & 0 & 2,11\cdot10^{10} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2,28\cdot10^{10} \end{bmatrix} \frac{N}{m^2}$$

Piezoelectric Matrix:

$$[\mathbf{e}]^T = \begin{bmatrix} 0 & -5,35 & 0 \\ 0 & 15,8 & 0 \\ 0 & -5,35 & 0 \\ 12,3 & 0 & 0 \\ 0 & 0 & 12,3 \\ 0 & 0 & 0 \end{bmatrix} \frac{N}{V}$$