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50. Internationales Wissenschaftliches Kolloquium
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Design of Multi-actuated Piezoelectric Micro-tools Using Topology Optimization

ABSTRACT

Micro-tools can have a wide range of application such as cell manipulation, microsurgery, nanotechnology equipment,etc. Micro-tools considered in this work consist of a multiflexible structure actuated by two or more piezoceramics that must generate different output displacements and forces in different specified points of the domain and directions, for different excited piezoceramics. The multiflexible structure acts as a mechanical transform by amplifying and changing the direction of the piezoceramics output displacements. Thus, the development of micro-tools requires to design micromechanisms with many degrees of freedom that perform complex movements without presence of joints and pins, due to manufacturing constraints of MEMS scale. In addition, when many piezoceramics are involved the coupling among movements becomes critical, that is, undesired movements may appear. This makes the design task very complex, which suggests that systematic design method, such as topology optimization, must be applied. Thus, in this work the topology optimization formulation was applied to design micro-tools actuated by many piezoceramics with minimum movement coupling. Essentially, the topology optimization method consists of finding the optimal material distribution in a design domain to extremize some objective function. The topology optimization method implemented is based on the CAMD approach where the pseudo-densities are interpolated in each finite element, providing a continuum material distribution in the domain. The optimization problem is posed as the design of a flexible structure that maximizes different output displacements (or grabbing forces) in different specified directions and points of the domain, for different excited piezoceramics. Different types of micro-tools can be obtained for a desired application. Among the examples, designs of a *XY* nanopositioner and a micro-gripper are considered.

INTRODUCTION

Microdevices have a wide range of applications in precision mechanics [1] such as cell manipulation, microsurgery tools, nanotechnology equipment, electronic microscopy instruments, lens positioner for laser interferometer, and mainly microelectromechanical systems (MEMS). Therefore, it consists in a technology in development whose applications are growing in the world. However, the development of these micro-tools requires the design of micromechanisms with many degrees of freedom that perform complex movements without presence of joints and pins, due to manufacturing constraints of MEMS scale. This can be achieved by applying the compliant mechanism technology. In a compliant mechanism the movement is given by the structure flexibility rather than the presence of pins and joints [2], which makes possible to transmit nanometers and micrometers displacements.

The microdevices considered in this work consists in a compliant mechanism (multi-flexible structure) actuated by two or more piezoceramics that generates different output displacements and forces in different specified points of the domain and directions, for different excited piezoceramics. We will call this microdevice a multi-actuated piezoelectric micro-tool. The multi-flexible structure acts as a mechanical transform by amplifying and changing the direction of the piezoceramics output displacements. Figure 1 illustrates two examples of this kind of device: a *XY* nanopositioner and a microgripper with 4 degrees of freedom (X and Y displacements, rotations, and open/close movement of gripper jaw).

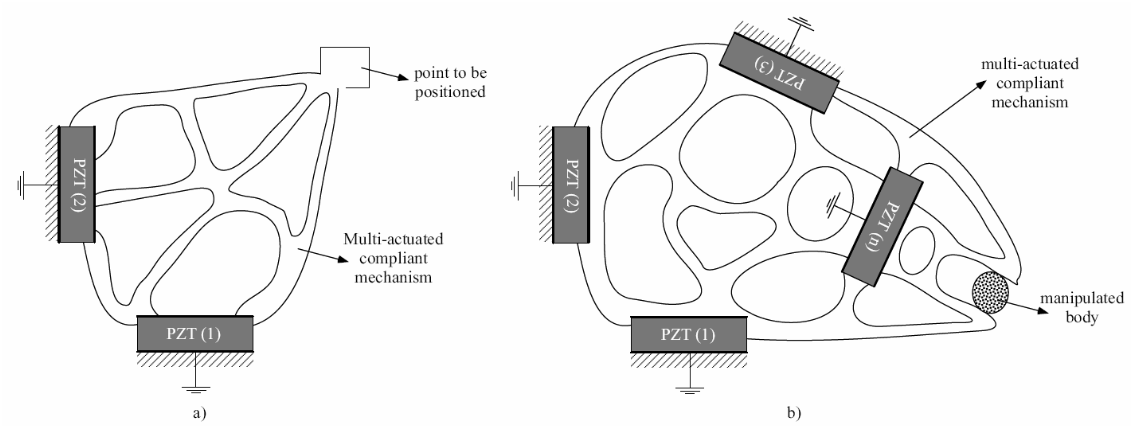

Figure 1:Concept of a multi-actuated flextensional piezoelectric devices. a) *XY* nanopositioner; b) Piezoceramics are responsible for *XY* displacements, rotation, and open/close movement of jaw.

The piezoelectric micro-tool design is very complex because when many piezoceramics are involved the movement coupling among them becomes critical, that is, movements in undesired directions may appear. This makes the design task very complex, which suggests that a powerful and systematic design method, such as topology optimization, must be applied to help to design these devices. Essentially, the topology optimization method consists in finding the optimal material distribution in a design domain to extremize some objective function. It has been successfully applied to a wide variety of problems, from the design of mechanical parts with high stiffness and low weight in the automotive and aeronautic industries [3] to compliant mechanisms [4,5], piezoelectric transducers [6,7], composite materials [8], and electrothermomechanical microdevices with multiple degrees of freedom [9].

In a previous work [10], a topology optimization formulation based on the homogenization design method was implemented to design micro-tools actuated by many piezoceramics with minimum movement coupling. However, it was difficult to obtain clear results, specially when considering many piezoceramics which it was believed to be related to the material model applied. Thus, in this work the topology optimization technique implemented is based on the CAMD ("Continuous Approximation of Material Distribution") approach, where pseudo-densities are defined for each finite element node and are interpolated by using the finite element (FE) shape functions inside of the finite element providing a continuum material distribution in the domain. It is a different approach than the traditional topology optimization formulation where the pseudo-density is approximated by piecewise constant in the FE implementation. This formulation seems to almost eliminate checkerboard problem [11, 12]. The optimization problem is posed as the design of a flexible structure coupled to the piezoceramics that maximizes different output displacements (or grabbing forces) in different specified directions and points of the domain, for different excited piezoceramics, including a coupling constraint among actuated displacements. A linear behavior of piezoceramics is considered. By designing other types of multi-flexible structures connected to the piezoceramics, novel types of piezoelectric micro-tools can be obtained.

Since designed micro-tools aim mainly MEMS applications, examples presented herein are limited to two-dimensional (2D plane stress), however, the proposed method is general and can be applied to three-dimensional (3D) models. As examples, designs of a *XY* piezoelectric nanopositioner [13] actuated by two piezoceramics and a micro-gripper actuated by three piezoceramics are described. These are very complex devices to be designed by using only physical intuition of the problem, simple analytical models [13], experimental techniques, or finite element analysis [14, 15]. The main difficulty is to reduce the coupling among the movements.

By applying this design method, new designs of micro-tools can be obtained with a good performance in a short term, avoiding the problems of designs based on empirical solutions that may take years to develop and usually involves only few people with large experience in the field. By developing systematic design methods, piezoelectric microdevice technology can be made more accessible and it can be easily spreaded among engineering community.

This paper is organized as follows. In section 2 and 3, a brief introduction about the continuous topology optimization method and the finite element formulation for piezoelectricity, respectively, is presented. In sections 4 and 5, the formulation of the topology optimization problem applied to micro-tool design and its numerical implementation are described. In section 6, micro-tool designs are presented and the results are discussed. In section 7, some conclusions are given.

CONTINUOUS TOPOLOGY OPTIMIZATION

Topology optimization is a powerful structural optimization technique that combines the Finite Element Method (FEM) with an optimization algorithm to find the optimal material distribution inside a given domain bounded by supports and applied loads that must contain the unknown structure [3]. The objective of topology optimization is to determine the holes and connectivities of the structure by adding and removing material in the extended fixed domain [8]. The finite element model domain is not changed during the optimization process which makes easy the calculation of derivatives of any function defined over the extended domain.

A main question to be addressed in topology optimization is how to change the material from zero (void) to one (material). The use of discrete values will lead to numerical instabilities caused by multiple local minima and should therefore be avoided. The problem can be relaxed by allowing the material to assume intermediate densities during the optimization. This is achieved by defining an appropriate continuous material model, where the formulation for intermediate materials defines the level of problem relaxation. Since the beginning of topology optimization implementation, the design variables that determine this mixture law were approximated by piecewise constant in their FE implementation, which means that the continuity of the material distribution is not realized between elements. Recent works [11, 12] have suggested considering the continuum distribution of the design variable inside of the finite element by interpolating it using the FE shape functions. In this case, the design variables would be defined for each element node instead of each finite element as usual. This formulation, known as CAMD seems to almost eliminate an old problem in topology optimization that it is the checkerboard problem. Thus, in this work, the topology optimization formulation employs a material model based on the SIMP ("Solid Isotropic Material with Penalization") method and the CAMD approach.

The traditional SIMP model [3] states that in each point of the domain, the material property is given by:

$$\mathbf{E^H} = \rho^{\mathbf{P}}\, \mathbf{E_0} \tag{1}$$

where $\mathbf{E^H}$ and $\mathbf{E^0}$ are the Young modulus of the homogenized material and basic material that will be distributed in the domain, respectively, ρ is a pseudo-density describing the amount of material in each point of the domain which can assume values between 0 and 1, and p is a penalization factor to recover the discrete design. For ρ equal to 0 the material is equal to void and for ρ equal to 1 the material is equal to solid material. Now, considering a discretized domain into finite elements, based on the concept of the continuum distribution of design variable based on CAMD method, equation (1) is considered for each element node, and the material property (Young modulus) inside each finite element is given by:

$$\rho(\mathbf{x}) = \sum_{i=1}^{n_d} \rho_I N_I(\mathbf{x})$$

where ρ_I is the nodal design variable, N_I is the finite element shape function and n_d is the number of nodes in each finite element. This formulation allows us to have a continuous distribution of material along the design domain instead of the traditional piecewise material distribution applied by previous formulation of topology optimization

FEM PIEZOELECTRIC MODELING

A general method such as the Finite Element Method (FEM) is necessary for the structural analysis since structure with complex topologies are expected. Therefore, the formulation of FEM for linear piezoelectricity is applied. This formulation is well-developed and only a brief description will be given here.

Micro-tools considered for design operate in quasi-static or low-frequency applications (inertia effects are neglected), thus, the finite element matrix system for modeling a linear piezoelectric medium considering a static analysis is given by [16]:

$$\begin{bmatrix} \mathbf{K_{uu}} & \mathbf{K_{u\phi}} \\ \mathbf{K}_{\mathbf{u}\phi}^{t} & -\mathbf{K}_{\phi\phi} \end{bmatrix} \begin{Bmatrix} \mathbf{U} \\ \phi \end{Bmatrix} = \begin{Bmatrix} \mathbf{F} \\ \mathbf{Q} \end{Bmatrix} \Longrightarrow \mathcal{KU} = \mathcal{Q} \quad (2)$$

where $\mathbf{K_{uu}}$, $\mathbf{K}_{\mathbf{u}\phi}$, and $\mathbf{K}_{\phi\phi}$ are the stiffness, piezoelectric, and dielectric matrices, respectively, and $\mathbf{F}$, $\mathbf{Q}$, $\mathbf{U}$, and ϕ are the nodal mechanical force, nodal electrical charge, nodal displacements, and nodal electric potential vectors, respectively [16].

DESIGN PROBLEM FORMULATION

The theoretical formulation of micro-tools design problem by using topology optimization follows the formulation presented in a previous work [10] and it will be briefly described here.

A micro-tool essentially consists in a coupling structure actuated by two or more piezoceramics [17, 18] where each piezoceramic is responsible for actuating a specific micro-tool movement. In addition, since the micro-tool is a compliant mechanism, there is always a coupling among actuated displacements, that is, when a piezoceramic is excited to generate a desired displacement, other undesired displacements will also be generated due to the structural coupling. Thus, in micro-tool design, it is desired that the generated undesired displacements must be as low as possible which is obtained by decoupling at most the actuated and undesired displacement.

Therefore, in the formulation of the micro-tools design optimization problem the objective is to design a device that generates different output displacements when actuated by different piezoceramics with a minimum coupling among these displacements. Thus, the objective function must be defined in terms of a combination of output displacements generated for a certain applied electrical charge to the electrodes of each piezoceramic, and it also must minimize the coupling among displacements, which can be achieved by including coupling constraints.

The quantity that relates the output displacement generated and electrical charge applied is called *mean transduction* $(L_2(\mathbf{U}_1,\phi_1))$ which has already been described in detail in the work of Silva *et al.* [6] related to the piezoelectric flextensional actuator design. The mean transduction concept is related to the electromechanical conversion represented by the displacement generated in region $\Gamma_{\mathbf{t}_2}$ in a certain direction due to an input electrical charge in region Γ_{d_1} of the piezoelectric medium. Thus, the larger $L_2(\mathbf{U}_1,\phi_1)$, the larger the displacement generated in this region in the $\mathbf{t}_2$ direction due to an applied electrical charge to region Γ_{d_1}. Therefore, the maximization of output displacement generated in a region $\Gamma_{\mathbf{t}_2}$ is obtained by maximizing the *mean transduction* quantity $(L_2(\mathbf{U}_1,\phi_1)\ or\ L_1(\mathbf{U}_2,\phi_2))$.

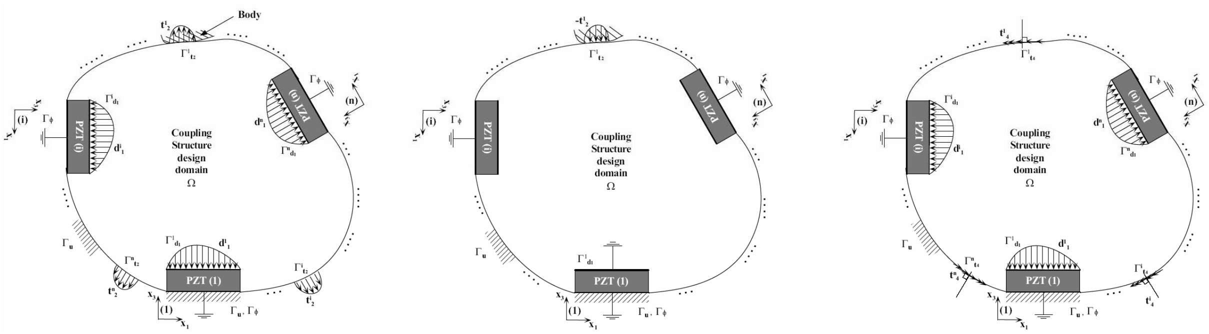

Figure 2: Coupling structure multi-actuated by piezoceramics. Load cases for calculation of: mean transduction (case a), mean compliance (case b) (only for piezoceramic "1"), and coupling constraint (case c).

Figure 2 illustrates the design domain of a coupling structure multi-actuated by *n* piezoceramics. Notice that each piezoceramic is polarized in the 3 direction considering its local axes as defined in figure 2. Since the coupling structure must generate different output displacements and forces (for example, grabbing force) in different specified points of the domain and directions, for different excited piezoceramics, the mean transduction must be calculated for each piezoceramic. Considering a piezoceramic "i", as described in figure 2a, the *mean transduction* for this piezoceramic is calculated by considering two load cases: the first one is related to the coupling structure response due to the application of a surface charge d_1^i on surface $\Gamma_{d_1}^i$ of the piezoceramic "i"; and the second one is related to an applied unit dummy traction $\mathbf{t}_2^i$ to region $\Gamma_{\mathbf{t}_2}^i$, in the same desired output displacement direction [6]. The superscript "i" refers to piezoceramic "i". The maximization of mean transduction maximizes output displacement generated in a region $\Gamma_{\mathbf{t}_2}^i$, therefore, satisfying the kinematic requirement.

Considering the FEM matrix formulation defined in the discretized domain and equilibrium equations (2), the mean transduction for piezoceramic "i" can be calculated numerically through the expression [6]:

$$L_2^i(\mathbf{U}_1^i, \phi_1^i) \quad = \quad \{\mathbf{U}_1^i\}^t \{\mathbf{F}_2^i\} = \{\phi_2^i\}^t \{\mathbf{Q}_1^i\} = \{\mathbf{U}_1^i\}^t [\mathbf{K}_{\mathbf{u}\phi}] \{\phi_2^i\} - \{\phi_1^i\}^t [\mathbf{K}_{\phi\phi}] \{\phi_2^i\} \tag{3}$$

since $\{\mathbf{U}_2^i\}^t \{\mathbf{F}_1^i\} = 0$ and $\{\phi_1^i\}^t \{\mathbf{Q}_2^i\} = 0$.

However, other structural function must be defined to provide enough stiffness between regions $\Gamma_{\mathbf{t}_2}^i$ and $\Gamma_{d_1}^i$, otherwise, the optimum solution obtained considering only the maximization of mean transduction may be a structure with very low stiffness. In addition, the coupling structure must resist to reaction forces generated (in region $\Gamma^i_{\mathbf{t}_2}$) by a body that the micro-tool is trying to move or grab. These goals can be achieved by minimizing the mean compliance between $\Gamma^i_{\mathbf{t}_2}$ and $\Gamma^i_{d_1}$ (see figure 2b). The mean compliance for each piezoceramic ``i" is calculated by considering a load case described in case (b) of figure 2 where a traction $\mathbf{t}^i_3 = -\mathbf{t}^i_2$ is applied to region $\Gamma^i_{\mathbf{t}_2}$ and the electrode surface $\Gamma^i_{d_1}$ is electrically grounded. Therefore, considering the FEM formulation in the discretized domain, the discrete form of mean compliance for piezoceramic "i" is given by the expression [6]:

$$L^i_3(\mathbf{U}^i_3, \phi^i_3) = \left\{\mathbf{U}^i_3\right\}^t \left\{\mathbf{F}^i_3\right\} = \left\{\mathbf{U}^i_3\right\}^t [\mathbf{K_{uu}}] \left\{\mathbf{U}^i_3\right\} + \left\{\mathbf{U}^i_3\right\}^t \left[\mathbf{K}^t_{\mathbf{u}\phi}\right] \left\{\phi^i_3\right\} \tag{4}$$

since $\{\phi^i_3\}^t \{\mathbf{Q}^i_3\} = 0$.

The coupling constraint is obtained by minimizing the corresponding mean transduction between actuated piezoceramic and generated undesired displacement. This will minimize an undesired displacement generated when a piezoceramic is excited. Therefore, the mean transduction $L^i_4(\mathbf{U}^i_1, \phi^i_1)$ between $\Gamma^i_{d_1}$ and the displacement tangent to $\Gamma^i_{\mathbf{t}_2}$ must be minimized (see figure 2c). The mean transduction for each piezoceramic "i" is calculated by using equation (3), however considering a load case described in case (c) of figure 2 where a traction $\Gamma^i_{\mathbf{t}_4}$, normal to $\Gamma^i_{\mathbf{t}_2}$, is applied to region $\Gamma^i_{\mathbf{t}_2}$.

Considering *n* piezoceramics, *n* mean transduction functions must be maximized for the kinematic requirement of micro-tool, *n* mean compliance functions must be minimized for the structural (stiffness) requirement, and *n* mean transduction functions must be minimized to minimize coupling among actuated movements. To find an appropriate optimal solution that can incorporate all design requirements, the following multi-objective function proposed in previous work [10] is applied to combine all these optimization problems:

$$\begin{aligned} \mathcal{F} &= w * \ln\left[-\frac{1}{\varepsilon_L}\ln\left[\sum_{i=1}^{n} e^{\left(-\varepsilon_L L^i_2(\mathbf{U}^i_1, \mathbf{\Phi}^i_1)\right)}\right]\right] \\ &\quad -\frac{1}{2}(1-w)\ln\left[\sum_{i=1}^{n}\alpha_i L^i_3(\mathbf{U}^i_3, \mathbf{\Phi}^i_3)^2 + \sum_{i=1}^{n}\beta_i L^i_4(\mathbf{U}^i_1, \mathbf{\Phi}^i_1)^2\right] \end{aligned} \tag{5}$$

$$
\begin{aligned}
0 \quad \leq \quad & w \leq 1 \\
& \sum_{i=1}^{n} \alpha_i = 1; \\
& \varepsilon_L > 0
\end{aligned}
\tag{6}
$$

Where ω, ε_L, α_i, and β_i are weight coefficients. The values of coefficients ω, ε_L, α_i, and β_i allow us to control the contributions of mean transduction (3), mean compliance, and mean transduction constraint functions (4) in the design. Thus, the final optimization problem is stated as:

$$
\begin{array}{lll}
\underset{\rho}{Maximize:} & \mathcal{F} & \\
subject\ to: & \mathbf{t}_3^i = -\mathbf{t}_2^i \quad (\Gamma_{\mathbf{t}_3}^i = \Gamma_{\mathbf{t}_2}^i) & i = 1..n \\
& \mathbf{t}_4^i \perp \mathbf{t}_2^i \quad (\Gamma_{\mathbf{t}_4}^i = \Gamma_{\mathbf{t}_2}^i) & \\
& \mathcal{K}_1\mathcal{U}_1 = \mathcal{Q}_1 & \mathcal{K}_2\mathcal{U}_2 = \mathcal{Q}_2 \\
& \mathcal{K}_3\mathcal{U}_3 = \mathcal{Q}_3 & \mathcal{K}_4\mathcal{U}_4 = \mathcal{Q}_4 \\
& 0 < \rho_{\min} \leq \rho < 1 & \\
& \Theta(\rho) = \int_S \rho dS - \Theta_S \leq 0 &
\end{array}
$$

where S is the design domain Ω without including the piezoceramic, Θ is the volume of this design domain, and Θ_S is an upper-bound volume constraint defined to limit the maximum amount of material used to build the coupling structure. The other constraints are equilibrium equations for piezoelectric medium [16] considering different load cases. The initial domain is discretized by finite elements and the design variables are the values of ρ_n (defined above) in each finite element node, defined only in the coupling structure domain. The lower-bounds $\rho_{\min} = 0.0001$ is necessary to avoid numerical problems such as singularity of the stiffness matrix in the finite element formulation. Numerically, regions with $\rho_{\min} = 0.0001$ have practically no structural significance and can be considered void regions. PZT is not included in the design domain, therefore elastic, piezoelectric and dielectric properties of corresponding PZT finite elements remain unchanged during the optimization and equal to property values given by Table 1. No filter technique is considered once checkerboard is not expected, however, the results may present mesh-dependency.

NUMERICAL IMPLEMENTATION

A flow chart of the optimization algorithm describing the steps involved is shown in figure 3. The software was implemented in C language. The design variables are the pseudo-density ρ_n defined only in the flexible structure domain (the piezoceramic is out of the design domain) which can assume different values in each finite element node.

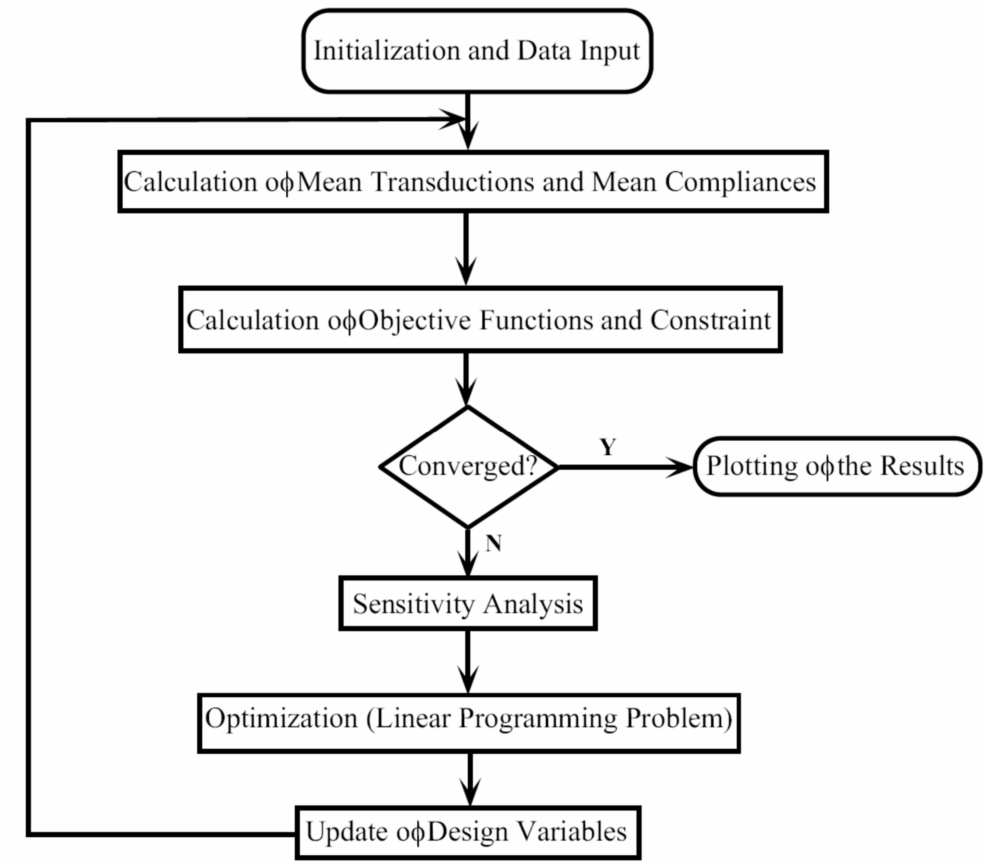

Figure 3: Flow chart of optimization procedure.

In this study, the mathematical programming method called Sequential Linear Programming (SLP) is applied to solve the optimization problem since there are a large number of design variables, and different objective functions and some constraints are considered [6, 19, 20]. The linearization of the problem (Taylor series) in each iteration requires the sensitivities (gradients) of the multi-objective function and constraints which are obtained by differentiating equation (5) in relation to the design variable ρ_n. This derivative will depend on gradients of mean transduction and mean compliance functions in relation to ρ_n derived by Silva *et al*. [6].

Suitable move limits are introduced to assure that the design variables do not change by more than 5-

15% between consecutive iterations. A new set of design variables ρ_n is obtained after each iteration, and the optimization continues until convergence is achieved for the objective function. The initial guess for design variables ρ_n consists of values of ρ_n obtained by initially solving the problem considering $\beta_i = 0$. The reason is that by including the mean transduction constraint the number of local minimums is increased. By starting with a material distribution obtained from a design without considering the mean transduction constraint, makes the optimization problem to start close to an appropriate local minimum solution.

RESULTS

Table 1 presents the piezoelectric material properties used in the simulations for all examples. $\mathbf{c}^E$, **e**, and $\boldsymbol{\varepsilon}^S$ are the elastic, piezoelectric, and dielectric properties, respectively, of the medium. The Young's modulus and Poisson's ratio of aluminum are equal to 106 *GPa* and 0.3, respectively. Two-dimensional elements under plane-stress assumption are used in the finite element analysis.

Table 1: Material Properties of PZT5

c_{11}^E (10^{10} N/m^2)	12.1	e_{13} (C/m^2)	-5.4
c_{12}^E (10^{10} N/m^2)	7.54	e_{33} (C/m^2)	15.8
c_{13}^E (10^{10} N/m^2)	7.52	e_{15} (C/m^2)	12.3
c_{33}^E (10^{10} N/m^2)	11.1	$\epsilon_{11}^S/\epsilon_0$	1650
c_{44}^E (10^{10} N/m^2)	2.30	$\epsilon_{22}^S/\epsilon_0$	1650
c_{66}^E (10^{10} N/m^2)	2.10	$\epsilon_{33}^S/\epsilon_0$	1700

The weight coefficient ε_L is equal to 10^8 for all examples. 100*V* is applied to piezoceramic electrodes. When the optimization process is complete, the result is a material distribution over the mesh with some intermediate values of density ("gray scale") that represents the presence of some intermediate material. The interpretation is achieved by simply applying a threshold value to density values. The results are shown by plotting the average density value for each element.

As a first example, the design of an *XY* piezoelectric nanopositioner will be considered. The design domain for this problem is shown in figure 4. It consists of two domains of piezoceramic that remain unchanged during the optimization and a domain *S* of Aluminum where the optimization is conducted. The domain of figure 4 has 8100 finite elements (rectangle discretized by a 90x90 mesh) and 8281 nodes. The mechanical and electrical boundary conditions are shown in the same figure.

The total volume constraint of the material Θ_{upp} is considered to be 25% of the volume of the whole domain Ω without piezoceramic (domain *S*). Therefore, the optimization problem starts in the feasible domain (all constraints satisfied).

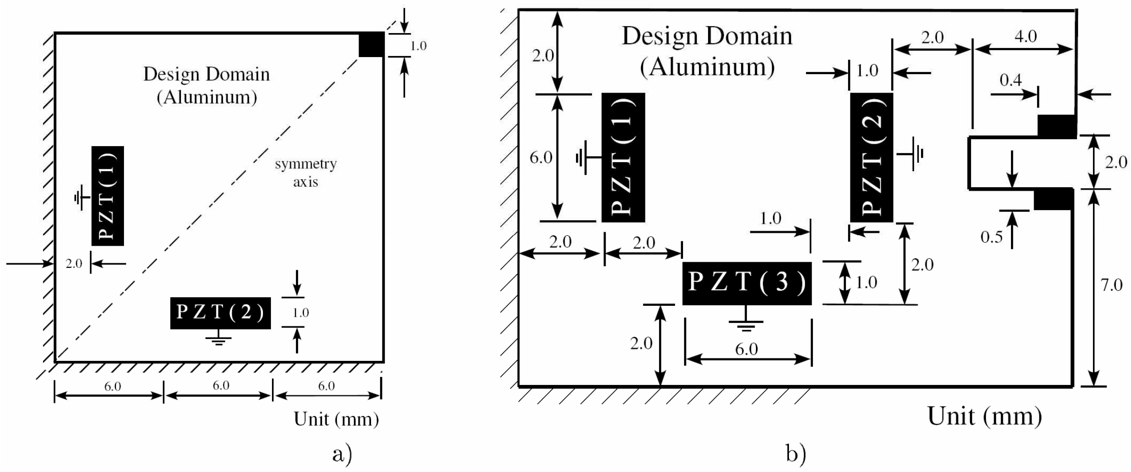

Figure 4: a) Initial design domain considered for *XY* piezoelectric nanopositioner design; b) Same, for piezoelectric micro-gripper design.

The load cases solved to calculate the multi-objective function for this problem are illustrated in figure 5. The optimization problem is defined as the maximization of the deflection at point *A* (upper right corner) in the direction of the dummy loads shown in figures 5b and d when electrical potential ϕ_1^1 is applied to the piezoceramic electrode 1, and electrical potential ϕ_1^2 is applied to the piezoceramic electrode 2, respectively (see figures 5a and c). To guarantee some stiffness in the moving direction and the applied force, the mean compliance at point *A* is to be minimized between A ($\Gamma_{t_2}^1$) and $\Gamma_{d_1}^1$, and A ($\Gamma_{t_2}^1$) and $\Gamma_{d_1}^2$, respectively (load cases of figures 5e and f). To constraint the coupling between *X* and *Y* displacements at point *A*, mean transductions related to the undesired displacements are minimized (load cases of figures 5g and h). Therefore, the eight load cases described in figure 5 are solved by FEM.

At first, an *YY* piezoelectric nanopositioner is designed by not taking into account the *X* and *Y* coupling constraint. The topology optimization problem was solved by considering coefficients ω, α_1, and α_2 equal to 0.5, 0.5, and 0.5, respectively, and coefficients β_1 and β_2 (see equation 5) both equal to 0.0. Thus, the coupling constraint is not active. The topology optimization result is shown in figure 6a and corresponding *Y* movements of interpreted nanopositioner result is shown in figure 6d.

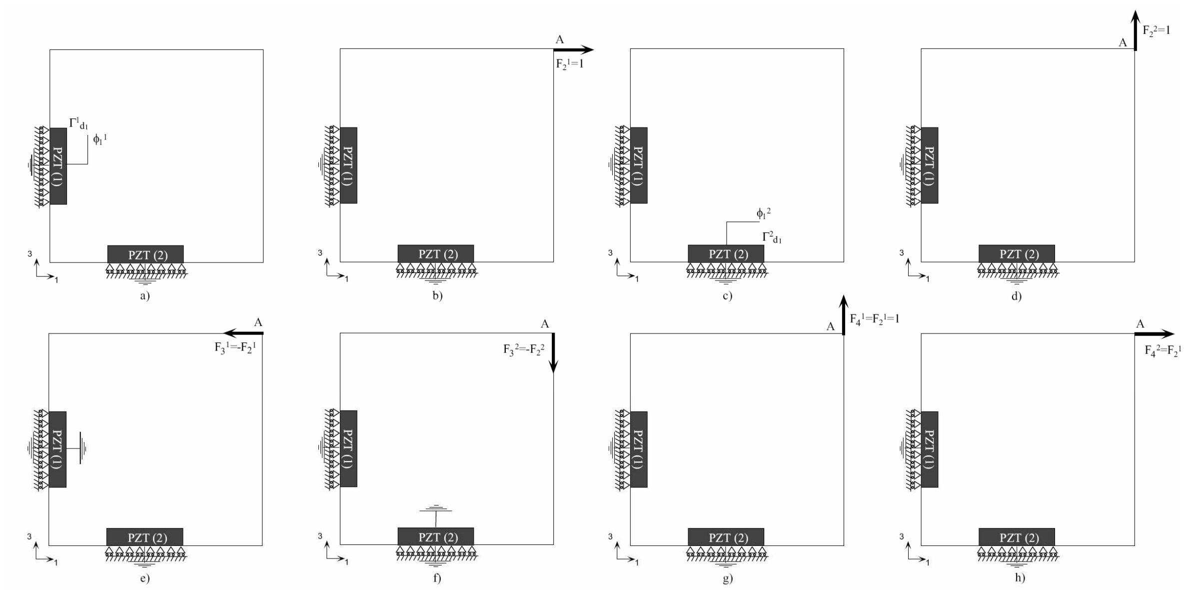

Figure 5: Load cases solved to compose the optimization problem for the example considered.

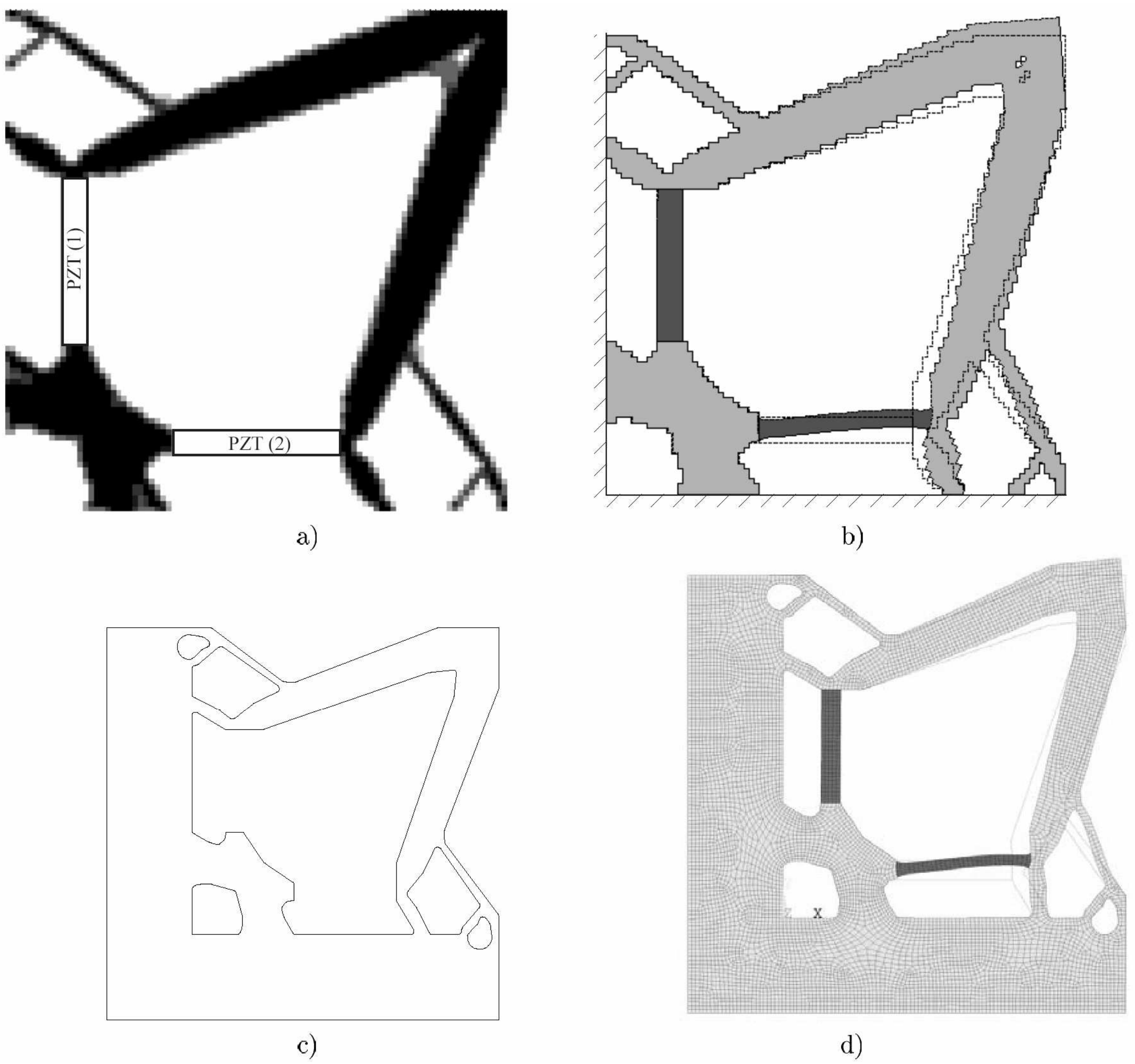

Figure 6: a) Topology optimization result ($\alpha = 0.5$, $\alpha_1 = \alpha_2 = 0.5$, $\beta_1 = \beta_2 = 0.0$); b) FEM deformed configuration; c) CAD interpretation; d) FEM deformed configuration of final actuator.

Table 2 describes X and Y displacements considering $100V$ applied to the piezoceramic and coupling factor R_{yx} for this nanopositioner. Coupling factor R_{yx} was calculated by dividing the desired displacement by the undesired displacement. A symmetry constraint was imposed.

Table 2: X and Y displacements ($100V$ applied) and coupling factors R_{yx}.

nanopositioner	u_x (nm)	u_y (nm)	R_{yx}
fig.6	-26.7	82.2	3.08
fig.7	-0.66	50.3	76.2

Then, the XY piezoelectric nanopositioner is designed by considering the coupling constraint. The topology optimization problem was solved by considering the same value for coefficients ω, α_1, α_2, however, now β_1 and β_2 (see equation 5) are equal to 0.01. The previous result was considered as an initial guess for density values in this problem. Thus, the topology optimization result for this XY piezoelectric nanopositioner is shown in figure 7a and corresponding Y movement of interpreted nanopositioner result is shown in figure 7d.

It is noticed from the figure that the XY coupling was considerably reduced in comparison with the previous design which did not consider the coupling constraint. X and Y displacements and coupling factor for this design are described in Table 2. It can be concluded that coupling was reduced however, in some cases, generated displacement was also reduced as also noticed in the previous work [10].

The next example considers the design of a piezoelectric micro-gripper with three degrees of freedom. The design domain consists of three piezoceramics and a domain S of Aluminum where the optimization is conducted, as described in figure 4b. The domain of figure 4b was discretized into 5200 finite elements and 5371 nodes. The mechanical and electrical boundary conditions are shown in the same figure. The piezoceramics are out of the design domain and each of them is responsible for a micro-gripper movement. Thus, piezoceramics 1 and 3 are responsible for jaw movement in the x and y direction, respectively, and the piezoceramic 2 is responsible for the "open-close" jaw movement. The material volume constraint Θ_{upp} is equal to 30%. This is a typical example where the coupling among movements is critical, and it is very difficult to obtain an intuitive design.

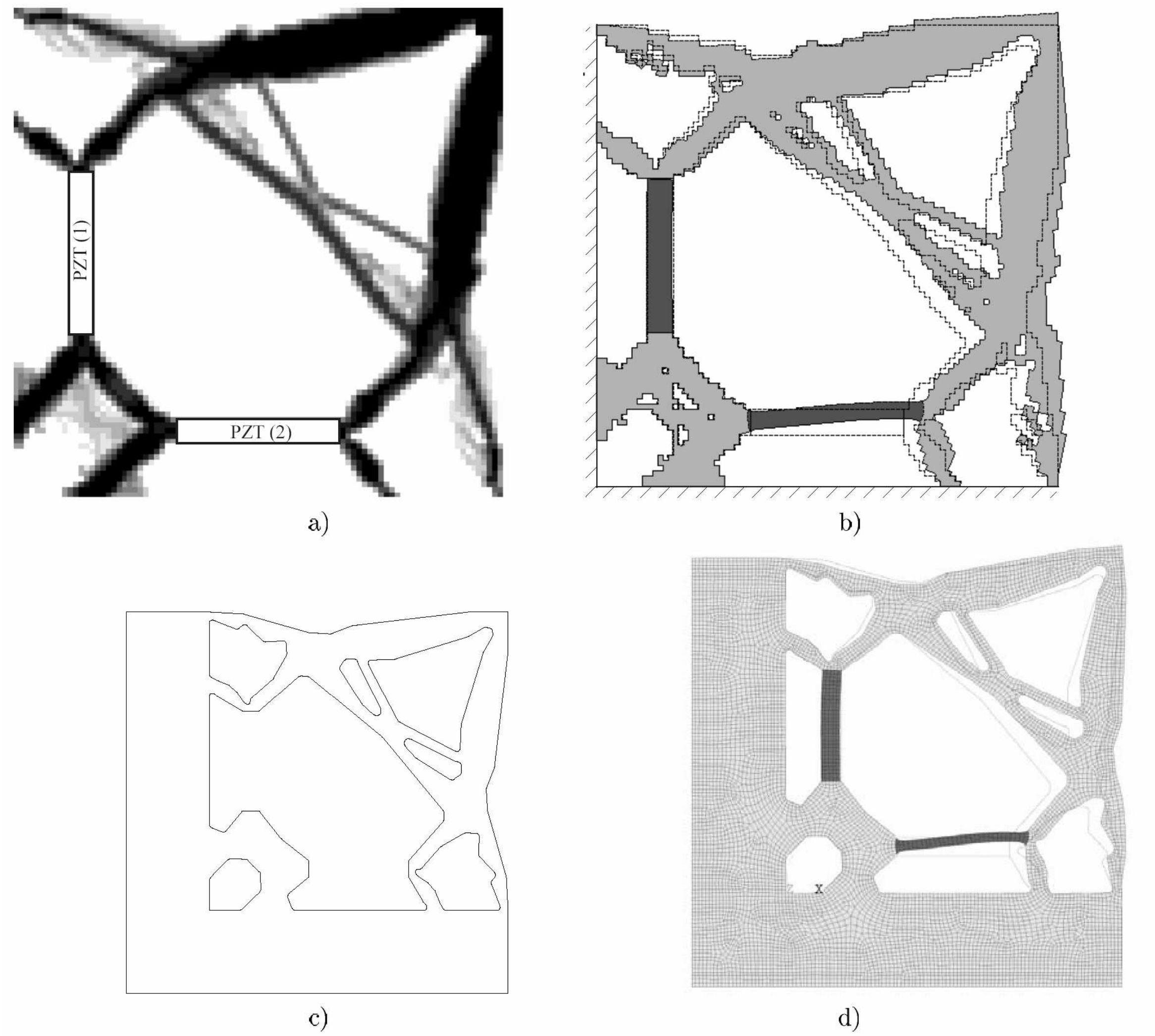

Figure 7: a) Topology optimization result considering coupling constraint ($\omega = 0.5$, $\alpha_1 = \alpha_2 = 0.5$, $\beta_1 = \beta_2 = 0.01$); b) FEM deformed configuration; c) CAD interpretation; d) FEM deformed configuration of final actuator.

In the design of the piezoelectric micro-gripper coefficients ω, α_1, α_2, and α_3 are equal to 0.5, 1/3, 1/3, and 1/3, respectively. Coefficients β_1 and β_2 are both assumed to be equal to 0.0, thus, the coupling constraint was not taking into account. The topology optimization result is shown in figure 8a and corresponding FEM simulations of movements considering interpreted micro-gripper result are shown in figures 8b, c, and d, respectively.

The result shows the robustness of the method which could obtain a coupling structure that generates all desired movements. In addition, even though the coupling constraint was not considered, the flexible structure has a very low coupling among movements.

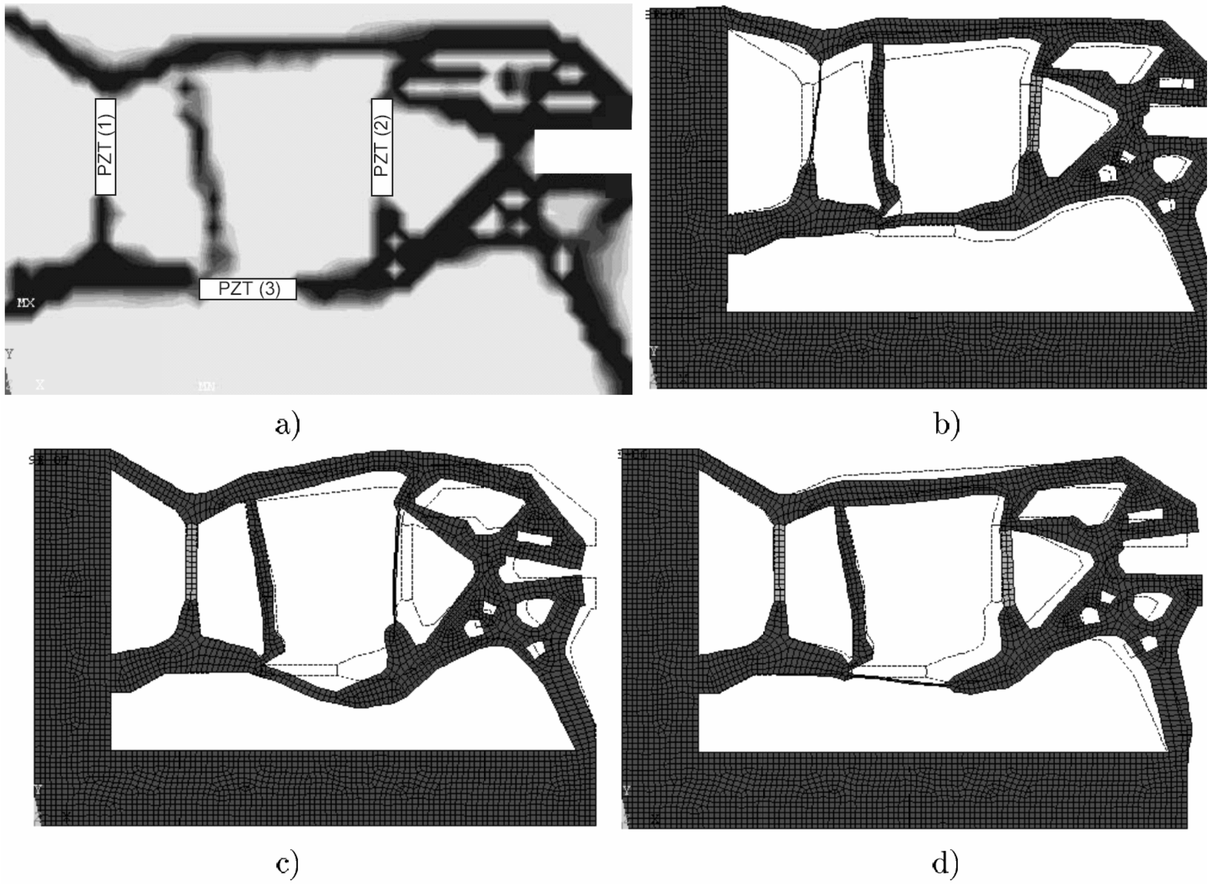

Figure 8: a) Topology optimization result ($\omega = 0.5$, $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$, $\beta_1 = \beta_2 = 0.0$); b) Movement generated by actuating piezoceramic 1; c) Same, for piezoceramic 3; d) Same, for piezoceramic 2.

CONCLUSIONS

The design of multi-actuated piezoelectric micro-tools was achieved by using the topology optimization method based on the continuous density approach [11, 12]. In this approach the pseudo-densities are defined for each finite element node and the continuum material distribution inside of the finite element is obtained by interpolating it using the FE shape functions.

The micro-tools considered consists in essentially a flexible structure connected to two or more piezoceramics (or stack of piezoceramics), that generates different output displacements and forces in different specified points of the domain and directions, for different excited piezoceramics. The applied optimizaton problem formulation allows us to reduce the coupling among the actuated displacements. Among the examples, designs of a *XY* piezoelectric nanopositioner and a micro-gripper were considered illustrating the potentiality of the method. The design method based on continuous density approach seems to be more robust and provides more clear results than a previous implementaton based on the homogenization design method [10].

The designed micro-tools can be manufactured in a mesoscale by using a wire EDM machine and in a microscale by using MEMS manufacturing techniques.

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