DESIGN, MANUFACTURING AND CHARACTERIZATION OF A NOVEL PIEZOELECTRIC MICROMIRROR

Vinícius Michelan Demarque, vinicius.demarque@gmail.com
University of São Paulo – Departament of Mechatronic and Mechanical Systems Engineering, Prof. Mello Moraes Avenue, 2231, São Paulo, Brazil

Emílio Carlos Nelli Silva, ecnsilva@usp.br
University of São Paulo – Departament of Mechatronic and Mechanical Systems Engineering, Prof. Mello Moraes Avenue, 2231, São Paulo, Brazil

Abstract. *Researches involving microactuators and micromirrors are mostly applied to bar code reading and image scanning. The most usual methods for micromirror actuation are the electromagnetic, the electrostatic, the thermal, and the piezoelectric actuation. The need of a high applied voltage for the electromagnetic and electrostatic actuations and the delay on the response of thermal actuation make the piezoelectric actuation superior because it requires lower applied voltage and it presents faster response. An application that needs a well-controlled displacement with accuracy in the order of* 10^{-6} *m is the optical data reading. For this purpose, a micromirror actuated by piezoelectric ceramics is used. This mirror can be rotated around his longitudinal and transversal axes (Θx and Θy), or displaced along his normal axis (Z), to perform the data reading in a given area based on the position displacement of the light beam reflected by the mirror. Thus, the objective of this work is to study the design, the manufacturing, and the characterization of a piezoelectric micromirror that generates a displacement normal to his plane (Z axis) and deflections Θx and Θy aiming digital data reading and optical scanner applications. In the design phase, an innovatory configuration of micromirror is suggested based on previous micromechanism described in the literature. The feasibility of the project is analyzed by finite element simulation using the software ANSYS. The 3D modeling allows the analysis of the micromirror displacements as a function of the applied voltage as well as obtaining the vibration modes and response frequency of the actuators. For manufacturing the actuator, the photolithography technique is applied. For the experimental characterization, a command is developed based on the MATLAB software and a joystick connected to the computer. A laser interferometer is applied to measure the displacements produced by the mirror. Finally, the simulated results are compared with the experimental ones.*

Keywords*: Micromirror, piezoelectric actuator, MEMS, CAE.*

1. INTRODUCTION

Researches involving microactuators and micromirrors are mostly applied to bar code reading and image scanning (Tsaur *et al.*, 2002). The most usual methods for micromirror actuation are the electromagnetic, the electrostatic, the thermal, and the piezoelectric actuation (Kobayashi *et al.*, 2005). The need of a high applied voltage for the electromagnetic and electrostatic actuations and the delay on the response of thermal actuation make the piezoelectric actuation superior because it requires lower applied voltage and it presents faster response.

Piezoelectric actuators developed fastly because of the need of an accurate displacement in many processes such as micro pumps (Vatanabe, 2008), data storage (Yee *et al.*, 2000), and optical switch (Wang and Liu, 2006). For example, an application that needs a well-controlled displacement with accuracy in the order of 10^{-6} m is the optical data reading. For this purpose, a micromirror actuated by piezoelectric ceramics is used. This mirror can be rotated around his longitudinal and transversal axes (*Θx* and *Θy*), as seen in Fig. 1, or displaced along his normal axis (Z), as seen in Fig. 2, to perform the data reading in a given area based on the position displacement of the light beam reflected by the mirror.

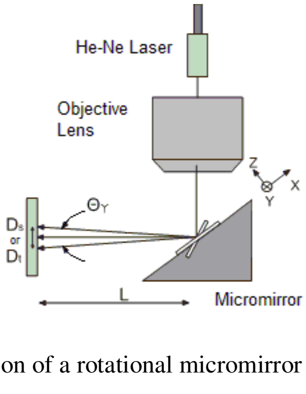


Figure 1. Reflection of a rotational micromirror (Tsaur *et al.*, 2002).

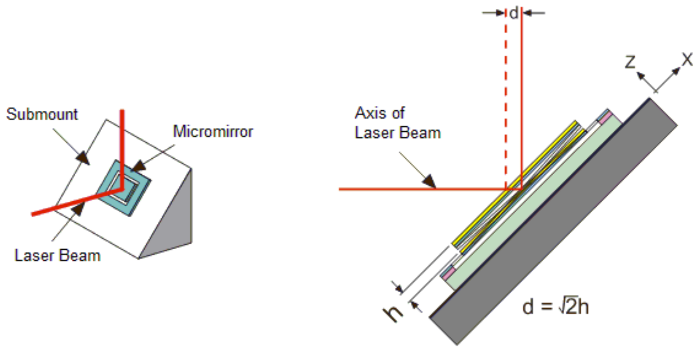


Figure 2. Reflection of the Z displacement micromirror (Yee *et al.*, 2000).

Among the two kinds of micromirror studied in the literature, the one that will be discussed in this work presents a displacement normal to his plane (Z axis) and deflections ϴx and ϴy. A novel configuration of micromirror is proposed, and its design, manufacturing, and characterization will be studied. The design is performed by using the finite element method, the prototype is controlled by using a joystick connected to a computer and the mirror displacement is measured by using a laser interferometer. The simulated results are compared with the experimental ones.

2. THEORETICAL ASPECTS

2.1. Piezoelectric materials

The constitutive equations of piezoelectric materials (Lambrecht and Cunha, 2007) are:

$$\mathbf{T} = \mathbf{c}^{E}\,\mathbf{S} - \mathbf{e}^{t}\,\mathbf{E} \tag{1}$$

$$\mathbf{D} = \boldsymbol{\varepsilon}^{S}\,\mathbf{E} + \mathbf{e}\,\mathbf{S} \tag{2}$$

Where:

T	Mechanic stress matrix
S	Mechanical deformation matrix
E	Electric Field vector
D	Electric displacement vector
$\mathbf{c}^{E}$	Elastic stiffness matrix obtained with constant electric field
e	Piezoelectric mechanic stress matrix
$\boldsymbol{\varepsilon}^{S}$	Dielectric matrix obtained with constant deformation

The 6 MM class of symmetry with Y axis polarization is considered in this work. In the plane state of mechanical deformation the equations can be written like this:

$$\begin{bmatrix} T_{XX} \\ T_{YY} \\ T_{ZZ} \\ D_X \\ D_Y \end{bmatrix} = \begin{bmatrix} c_{11}^{E} & c_{13}^{E} & 0 & 0 & e_{31} \\ c_{13}^{E} & c_{44}^{E} & 0 & 0 & e_{33} \\ 0 & 0 & c_{13}^{E} & e_{15} & 0 \\ 0 & 0 & e_{15} & -\varepsilon_{11}^{S} & 0 \\ e_{31} & e_{33} & 0 & 0 & -\varepsilon_{33}^{S} \end{bmatrix} \begin{bmatrix} S_{XX} \\ S_{YY} \\ S_{XY} \\ -E_X \\ -E_Y \end{bmatrix} \tag{3}$$

In Eq. (3), the direction 1 represents the X axis and the direction 3 represents the Y axis. The non null middle matrix values need to be given to the FEM software.

2.2. Bilaminar actuators

The principle of a piezoelectric actuator is that the piezoelectric ceramic contracts or expands when excited by an electric voltage. This ceramic, bonded in a flexible material, cannot contract or expand freely, but it deforms together with the flexible material. In a bilaminar actuator, two ceramics are used, one on each side of the flexible material, as shown in Fig. 3.

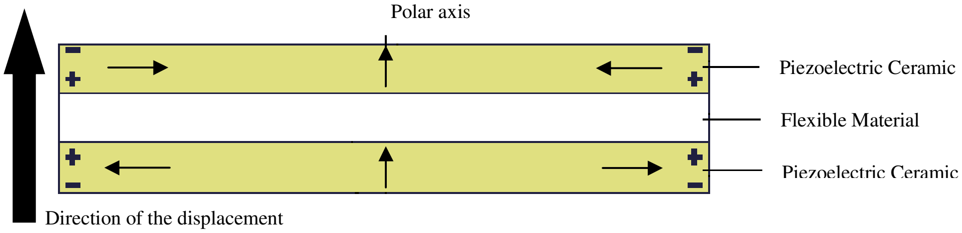


Figure 3. Properties of a piezoelectric ceramic in a bilaminar actuator.

The flexible material is used as support material and electrode. The two piezoelectric ceramic, one on each side of the flexible material, increases the amplitude of the displacement.

2.3. Piezoelectric Finite Element Method

In a piezoelectric material (domain), the displacement **u** and the potential electric field **Φ** must be determined. These two parameters satisfy the dynamic equilibrium equation in the matrix form (Uchino, 2003):

$$\begin{cases} \mathbf{M_{uu}\,\ddot{u} + K_{uu}\,u + K_{u\Phi}\,\Phi = F} \\ \mathbf{K_{u\Phi}}^{t}\,\mathbf{u + K_{\Phi\Phi}\,\Phi = Q} \end{cases} \tag{4}$$

Where:

$\mathbf{M_{uu}}$	Mass matrix
$\mathbf{K_{uu}}$	Elastic stiffness matrix
$\mathbf{K_{u\Phi}}$	Piezoelectric stiffness matrix
$\mathbf{K_{\Phi\Phi}}$	Dielectric stiffness matrix
F	Mechanical forces
Q	Electric charges

2.4. Photolithography

This method is widely used nowadays for micromachining and integrated circuit manufacturing. It is divided in several steps.

The first step is the resist application. Resist is a solution of an organic polymer (base resin), a sensitizer and a casting solvent that is deposed over the substrate wafer. The polymer changes structure when exposed to radiation. The resist protects parts of the substrate and exposes parts that will be submitted to etching or material addition.

In the next step the mask is placed over the substrate. The stencil used to generate a desired pattern in resist coated wafers is called mask (Madou, 2002). The exposure of UV radiation is made before the development.

Development transforms the latent resist image formed during the exposure into a relief image which will serve as a mask for further subtractive and additive steps. In this work, the last step is a wet etching to manufacture the micromirror.

3. METHODOLOGY

The simulation of the micromirror is performed using the ANSYS software to check the prototype feasibility. The micromirror is supported by two hinges symmetrically located in the middle of the mirror. The cantilevers are the piezoelectric bimorph actuators. The micromirror and the hinges are made by copper. The actuator is made by carbonfiber and piezoelectric ceramics with copper electrodes.

In the simulation, the actuators and the micromirror are represented because these are the only flexible components of the system. To generate the mesh, two elements had to be chosen. To simulate the copper material, the SOLID45 element is used. It is an element used for modeling 3-D solid structures. The element is defined by eight nodes having three degrees of freedom at each node that are the translations in the X, Y and Z axis. The piezoelectric material is simulated using the SOLID98 Tetrahedral Coupled-Field Solid. This is a 10 node element with a 3-D magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. In this work, only the translations in the X, Y and Z axis and the electric potential are used as degrees of freedom for each node. When used in piezoelectric analyses, this element has large deflection and stress stiffening capabilities.

The size of the element is an important parameter for the analysis. The more regular is the structure mesh the better are the results in the FEM analysis. The thickness of the micromirror is equal to 0.1 millimeters and the thickness of each layer of the actuator is equal to 0.2 millimeters. As dimensions of the micromirror and the actuators are multiples of the thickness, the element size used in the simulation is equal to the smallest thickness 0.1 millimeters. Figure 4 illustrates the mesh of the actuators and the micromirror.

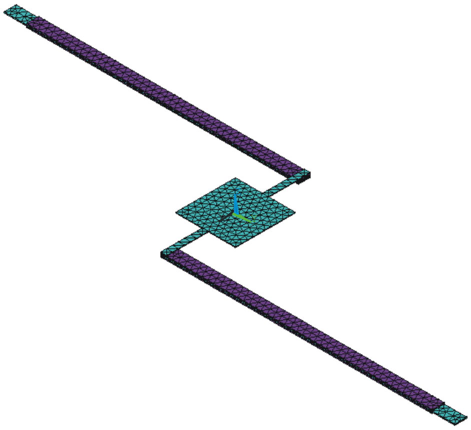


Figure 4. The micromirror mesh.

Figure 5 shows the design of the prototype and the Tab. 1 presents the material list.

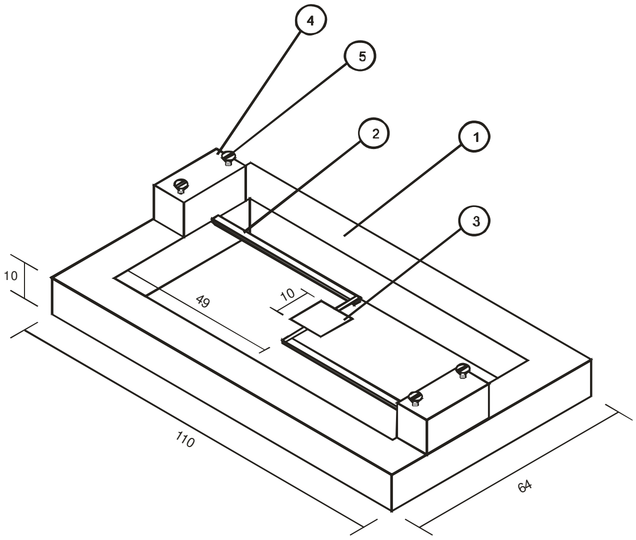


Figure 5. Design of the prototype.

Table 1. List of materials used in the prototype.

Number	Description	Material	Quantity
1	Base	Acrylic	1 piece
2	Piezoelectric actuators	Copper, carbon fiber and piezoelectric ceramic PZT5A	2 pieces
3	Micromirror	Copper	1 piece
4	Crimping	Aluminum	2 pieces
5	Screw M2.5 x 25 mm	Steel	4 pieces

4. SIMULATION RESULTS

Three analysis are performed in ANSYS software, the static analysis, the modal analysis and the harmonic analysis. The static analysis simulates the behavior of the micromirror when an electric voltage is applied to the piezoelectric ceramic surface generating the micromirror displacement. The modal analysis allows checking resonance frequency and the vibrating modes of the micromirror. The harmonic analysis determines which vibration mode corresponds to a piezoelectric mode, that is, a mode obtained by applying electric voltage to the actuators.

4.1. Static analysis results

Simulations are done for the vertical displacement and rotational cases. Applied voltages values equal to 10, 60, 100 and 600 volts are considered. Table 2 presents the obtained results.

Table 2. Static analysis results.

Volts (V)	Angle (°)	Displacement (μm)
10	3.2315×10^{-2}	5.34
60	1.9423×10^{-2}	32.0
100	3.2314×10^{-1}	53.4
600	1.9416	320

Figure 6 shows the graphic of electric voltage versus angle for the rotational case.

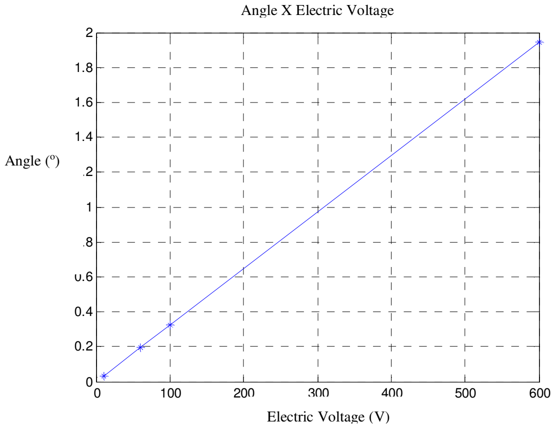


Figure 6. Angle X Electric Voltage for the rotational micromirror case.

Figure 7 presents the electric voltage versus displacement on the Z axis for the vertical displacement case.

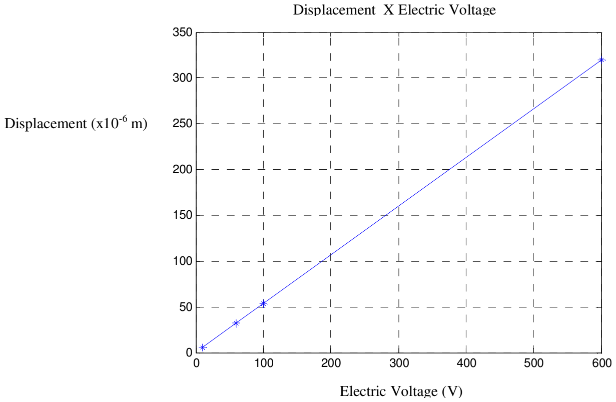


Figure 7. Displacement X Electric Voltage for the vertical micromirror case.

Both curves are completely straight, showing that the deformation of a piezoelectric ceramic is linearly proportional to the electric voltage applied to its surfaces.

4.2. Modal analysis results

The modal analysis demonstrates the operational speed of the micromirror. The higher the resonant frequency, the faster the micromirror can work without reaching the resonant mode. Table 3 presents the results of modal analysis.

Table 3. Modal analysis results.

Vibrating modes	Frequency (Hz)
1st Mode (1st piezoelectric)	222.84
2nd Mode (not piezoelectric)	448.71
3rd Mode (not piezoelectric)	525.49
4th Mode (2nd piezoelectric)	1222.0
5th Mode (not piezoelectric)	1256.8

4.3. Harmonic analysis results

The harmonic analysis helps to identify which vibrating mode is a piezoelectric mode. In this work two simulations are done, one considering the frequency range that includes the first two vibrating modes and another including the three next modes. Just the first five modes are simulated because the next modes clearly either do not characterize a piezoelectric vibrating mode or they correspond to too high frequencies. Figure 8 shows the graphics obtained by this analysis.

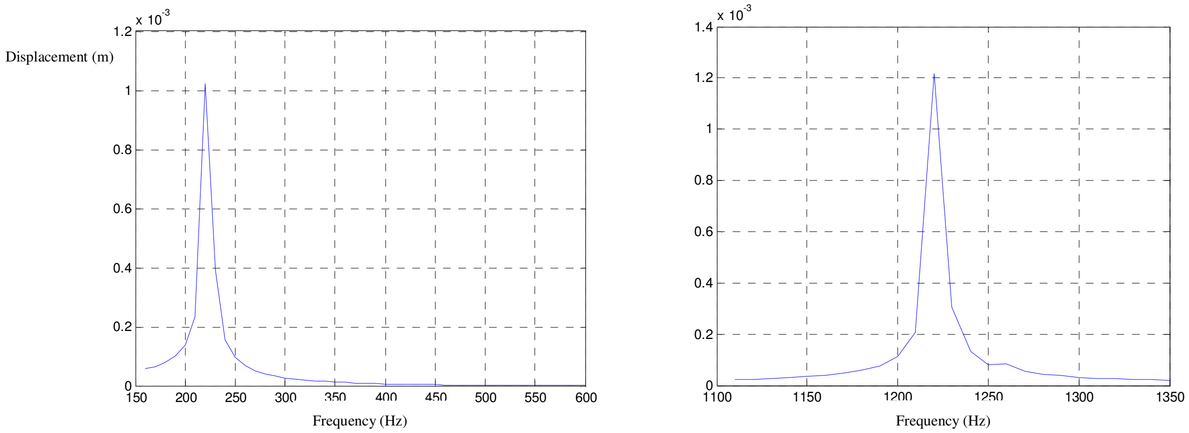
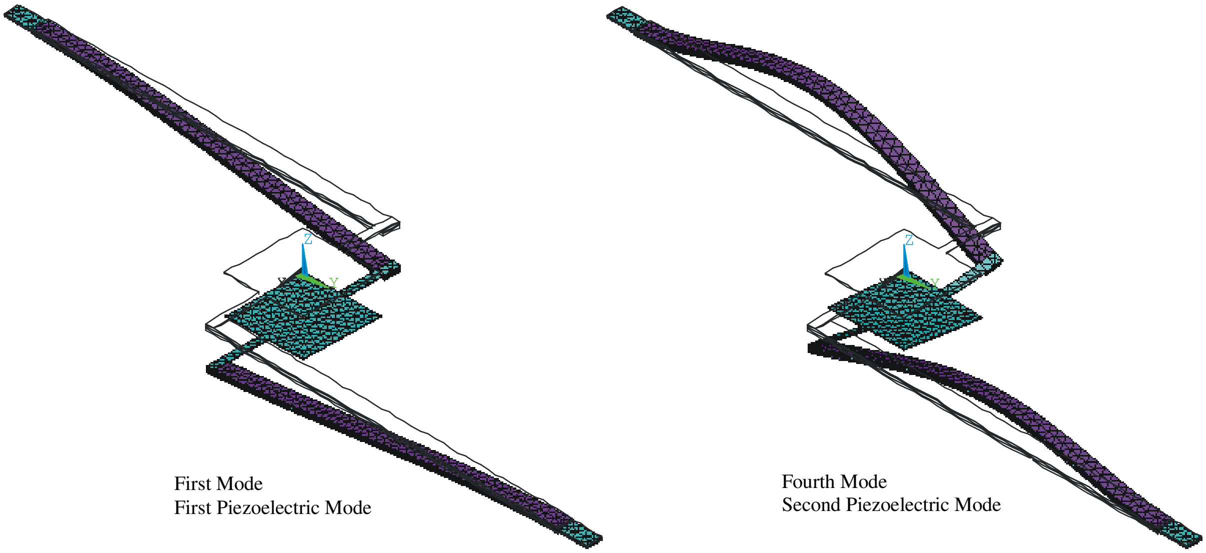


Figure 8. Harmonic analysis from 150 to 600 Hz and from 1100 to 1350 Hz.

From the graphics, the piezoelectric vibrating modes can be identified as the first (222.84 Hz) and the fourth (1222.0 Hz) modes. Thus, the work speed of the micromirror must be lower than 222.84 Hz, high enough to satisfy the requirement of the optical data storage (Yee *et al.*, 2000). Figure 9 presents the micromirror first and fourth modes of vibration (first and second piezoelectric modes of vibration).



First Mode
First Piezoelectric Mode

Fourth Mode
Second Piezoelectric Mode

Figure 9. Micromirror first and fourth modes of vibration.

The vibrating mode frequencies are sufficiently high for the device to operate with many cycles in a second without reaching the resonance maintaining a well controlled displacement. It permits a fast data reading according to the micromirror.

5. MICROMIRROR COMMAND

The command of a piezoelectric actuator is obtained by applying an electric voltage that results in the deformation of the ceramic and the actuator displacement. This command could be direct, by adjusting manually the electric source to supply the desired electric voltage. However, this work uses a remote command, where a joystick and an interface are used to operate the actuator.

The joystick provides data to the computer through an USB (*Universal Serial Bus*) input. These data are used by the interface software MATLAB that operates the electric source through a GPIB (*General Purpose Interface Bus*) board. The source terminals are connected to the piezoelectric ceramic that actuates the micromirror. The displacement of the micromirror is measured by a laser interferometer. Figure 10 shows the micromirror's command.

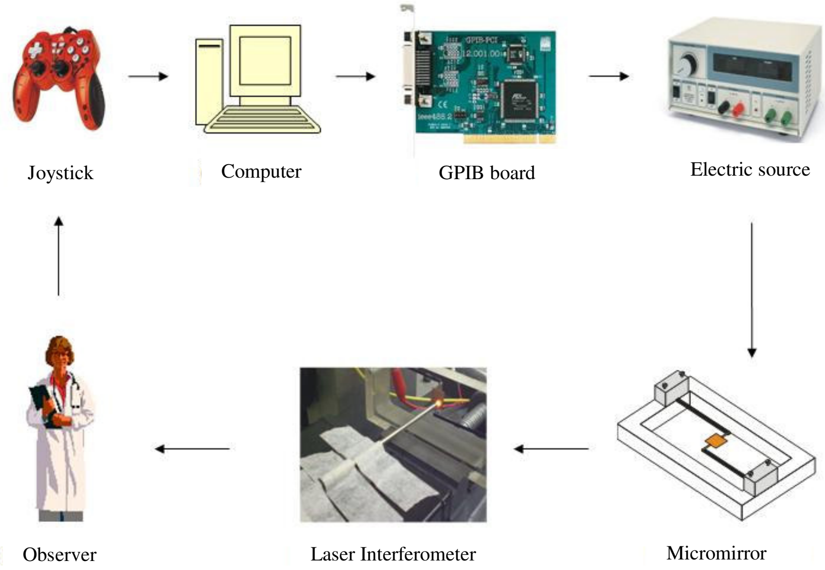


Figure 10. Micromirror command.

6. RESULTS

Figure 11 presents the micromirror device and the command devices.

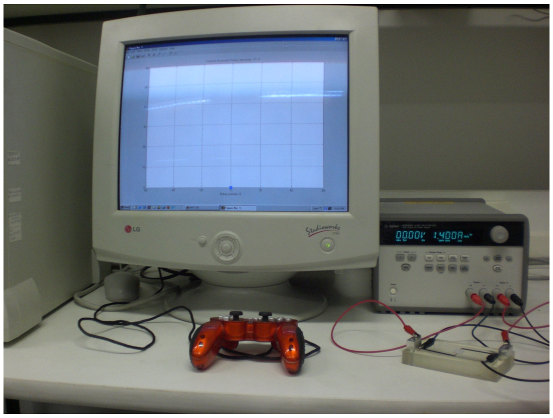


Figure 11. Command devices of the micromirror.

Figure 12 shows the graph of displacement versus electric voltage obtained by simulation compared to the one obtained by the interferometer.

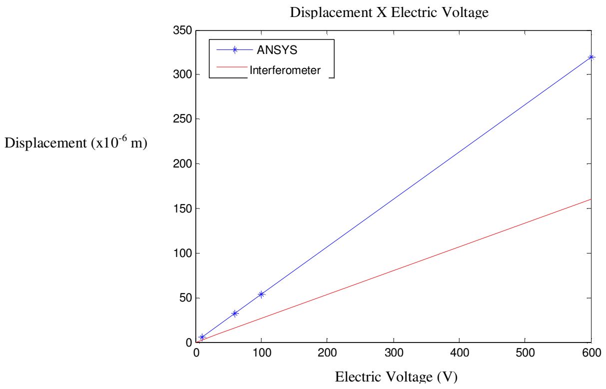


Figure 12. Displacement X Electric Voltage of the micromirror.

The displacement of the micromirror obtained by the interferometer is nearly half of the obtained by the simulation. This is because some factors are not considered on the simulation, such as the bending between the ceramic and the cantilever, the finish layer over the actuators, or failures or irregularities in the machining process among others. All these factors make the prototype generate smaller displacements.

7. CONCLUSIONS

The design of the proposed prototype is feasible, showing compatibility between the simulation results and the expected ones. The expected displacement for piezoelectric ceramics is in the order of 10^{-6} m for an applied electric voltage in the order of 10 volts (Yee *et al.*, 2000).

The displacements of the micromirror can be measured by using an interferometer and the applied voltage is in the order of 60 volts.

Even though smaller, the displacements obtained by the prototype are of the same order of magnitude of the ones obtained by the FEM simulation at ANSYS which shows the efficiency of this kind of analysis in the design phase of MEMS.

The command of the micromirror presented fast and accuracy responses after the joystick actuation. It is possible to see the gradual variation of the electric voltage as the cursor of the joystick is moved as well as the micromirror displacement when the electric voltage varies.

Continuing this work, a novel micromirror configuration will be proposed with more actuators. The analysis will be done in the ANSYS software with shell and solid elements. A parametric optimization will be performed to optimize the actuator dimensions to maximize the displacement and the angle generated by the mirror.

8. ACKNOWLEDGEMENTS

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