# MODELING AND CONTROL OF A MICROGRIPPER BASED ON ELECTROMAGNETIC ACTUATION

Veronica DESPA[1], Adrian CATANGIU[1], Ioan Alexandru IVAN[2], Valentin GURGU[1], Mihai ARDELEANU[1]

[1)] Valahia University of Targoviste [2)] Université de Lyon, France

Email: dumiver@yahoo.com, acatangiu@yahoo.co.uk, ioan.alexandru.ivan@gmail.com, gurguvalentin@yahoo.com, mihaita.nicolae.ardeleanu@gmail.com,

***Abstract*** *Design, fabrication and tests of a compliant flexure based microgripper were performed. The bending force is applied by using a mixt interaction between two solenoids and two permanent magnets rigid fixed on cantilevers. Micromanipulation tests were conducted in order to confirm the mathematical model developed for device simulation The simulation and experimental data are in a good agreement and have proven accuracy of device control system.*

**Keywords:** *microgripper, solenoid magnet interaction modeling, magnet magnet interaction, electromagnetic actuation force.*

## 1. INTRODUCTION

In order to manipulate objects with small dimensions there are used microgrippers in various constructive shapes, with manipulation systems based on shape memory effect, piezoelectric, electromagnetic etc. One of the major problems in the operation of a manipulator is achieving reproducibility of movements (hysteresis can become a problem, for example, in case of the SMA actuators).

The microgripper whose function is analyzed, presents a mixed type of handling: electromagnetic for the moving in xOy plane, respectively, piezoelectric in xOz plane.

Figure 1 shows the outline constructive design of the magneto-piezoelectric device for micro-manipulation. Effector elements are two beams rigidly attached to the frame whose movement is achieved by bending owed to the magnetic interaction between solenoid and the conjugated permanent magnet rigidly fixed on the active arm.

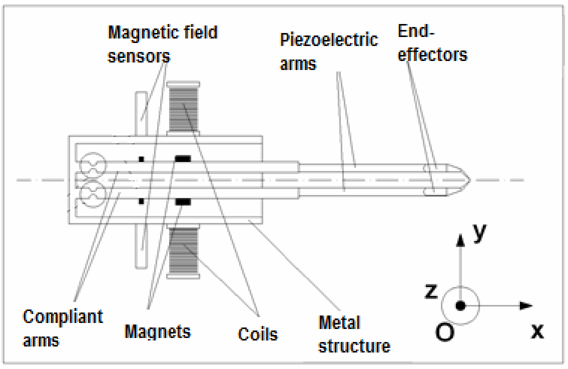


**Fig.1. Schematic representation of the magneto-piezoelectric device for micromanipulation**

The piezoelectric arms provides movement on the perpendicular direction to the plane of the figure. End effectors take contact with the object to manipulate (fig.2).

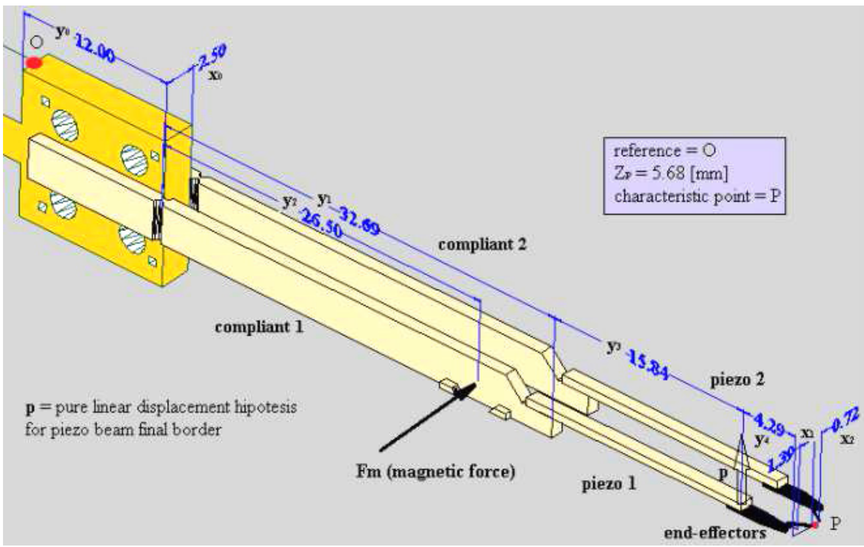


**Fig.2. The system of the two actuators groups**

## 2. THE ACTUATION PRINCIPLE

The compliant arm moves as a result of the interaction between three independent elements:

- Interaction between permanent magnets rigidly fixed to the arms, has as effect a bending of beam, position which becomes steady (0 relative);
- Magnetic force $F_m$ (Fig.3), as a result of the interaction between the magnetic field of a coil (solenoid) and the permanent magnet fixed to the conjugated arm;
- Mechanical elasticity which ensures the return to the equilibrium position (0 relative) of the arm in case of the current through the solenoid is zero;

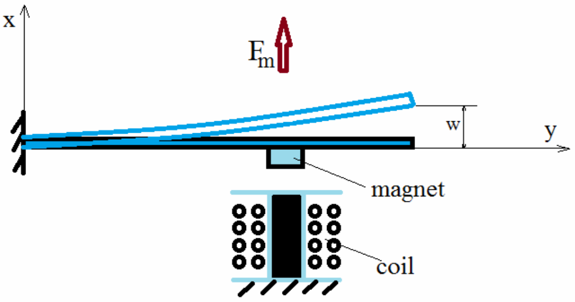


**Fig.3. Working principle of the compliant element**

Because the displacements are extremely small (tens micrometers) the deformations of compliant arm are in the elastic range.

For electromagnetic acting of the mechatronic device we used high-energy permanent magnets NdFeB type S-04-1,5-N with the following characteristics:

- Diameter d = 4 mm
- Height h = 1,5 mm
- Magnetic flux density (magnetic induction) $B_m$ = 1,35 T.

Caracteristics of electromagnets:

- number of turns 400 each;
- coil diameter dem = 9,5 mm,
- overall height hem = 9mm, which includes two spacer rings, each having gi = 1 mm thick.

Iron core of the coil has the same radius as the permanent magnet.

The distance between each magnet and the associated coil is $x_2$ = 1,3 mm, and the total distance between two magnets is $d_1$ = 4,3 mm.

The position of permanent magnets and associated coils is shown in Figure 4.

In an simplified approach, each arm is subjected to the action of two forces by magnetic nature: attraction/rejection generated by the electromagnet (coil), respectively, the attraction force between the permanent magnets.

Given the proximity of permanent magnets ($d_1$ = 4,3 mm), static attraction force (without electricity) cannot be ignored.

The magnets have been arranged in parallel to the magnetization (in the same way N-S, N-S) in such a way as to attract each other.

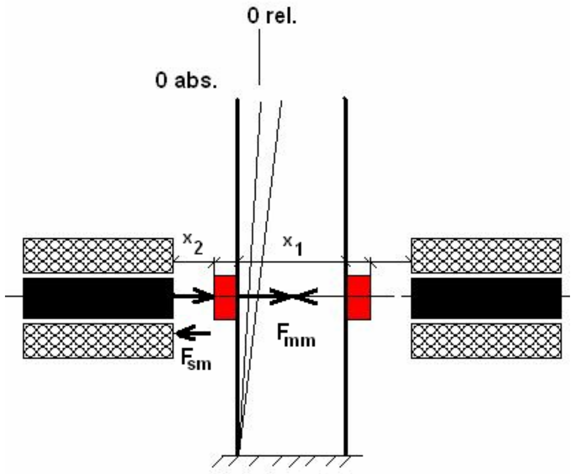


**Fig.4. The position of permanent magnets and solenoids that operates the actuator**

**Interaction magnet - magnet and magnet - solenoid**

In literature, the problem of attraction force between two permanent magnets is analized from several perspectives.

Each approach is based on general interaction between a permanent magnet and a magnetizable half-space that can be created by another permanent magnet or a solenoid. Vorohobov [1] develops the theory of this type of interaction and shows the expressions of the attraction force between two magnets placed at different distances. The results of numerical integration of the force are strictly dependent on the boundary conditions.

One of the methods of assessing the interaction between two uniform magnetized objects is **the filament method**, in which each element is considered a current-carrying coil. The interaction force between the two coils is given by the following relation [2]:

$$F_f(r_1, r_2, x) = \mu_0 I_1 I_2 x \sqrt{\frac{m}{4 r_1 r_2}} \left[ K(m) - \frac{m/2 - 1}{m - 1} E(m) \right] \quad (1)$$

where r1 and r2 are the coil radius and x is the axial distance between them. The functions K(m) and E(m) are the complete first and second elliptic integrals respectively with parameter *m* and $I_1$, $I_2$ are the currents through the coil.

$$m = \frac{4 r_1 r_2}{[r_1 + r_2]^2 + x^2} \quad (2)$$

By using the 'filament method', equations (1) and (2) can be used to calculate the force between any arrangement of coaxial solenoids.

The force between coils is attained by computing the interaction force between each pair of turns of the separate coils (as sum of this interaction) [2].

In case of interaction between two permanent magnets or between a magnet and a solenoid, the permanent magnet is associated with a solenoid with a number of turns

which provide the magnetic flux density B equivalent to the solenoid one.
Another way to approach the problem of interaction between magnets is **integral method**.
An integral expression for the force resulted from the interaction of a solenoid with a magnet is derived by using the theory of Furlani [3].
It is considered that the solenoid can be modeled as a volumic current density and the permanent magnet as a surface current density around the circumference.
A solenoid with the volumic current density J generates a magnetic field B at a distance of $d_1$ given by the integral over the whole coil volume $V_c$ [2].

$$B(d_1)=\frac{\mu_0}{4\pi}\int_{V_c}\frac{J(d_2)\times[d_2-d_1]}{|d_2-d_1|^3}dV_c \tag{3}$$

The analytical expression of the force exerted by the magnetic field on a permanent magnet [2]:

$$F_z=\frac{B_m\cdot N\cdot I}{l_c[R_c-r_c]}\int_{-l_c/2}^{l_c/2}\int_{r_c}^{R_c}\sum_{e_1}^{\{-1,1\}}[e_1\cdot m\cdot f_z]\,dr_2dz_2 \tag{4}$$

where:

$$f_z=\left[1-\frac{1}{2}m_1\right]\cdot K(m_1)-E(m_1)$$

$$m_1=\frac{4R_m\cdot r^2}{m^2},\quad m^2=[r+r_2]^2+\left[z+\frac{1}{2}e_1l_m-z_2\right]^2$$

where:
N – number of turns
I - the current in the coil
r - the magnet radius
$R_c$, $r_c$ – the coil external radius, respectively the coil internal radius.
The analytical integration method is also based on the first and second order elliptic integrals.
Vokoum [4] uses a similar approach and presents an analytical expression for calculating the interaction force between two cylindrical permanent magnets in the conditions of a uniform-considered magnetization.
The formula for the simplified numerical integration in this case describes the axial interaction force between two permanent magnets of radius r and length $h_1$ for the specific local conditions of the analyzed device (5):

$$F(x_1)=\frac{\pi\cdot K_d}{2}r^4\ p_1=\frac{\pi B_m^2}{4\mu_0}r^4p_1 \tag{5}$$

where:

$$p_1=\left[\frac{1}{x_1^{\ 2}}+\frac{1}{(x_1+2h_1)^2}-\frac{2}{(x_1+h_1)^2}\right]$$

$\mu_0$ – magnetic permeability of air (the nature of space between the magnets), $4\pi\times10^{-7}$ T·m/A
$K_d$ – the magnetostatic energy constant

$$K_d=\frac{\mu_0M^2}{2},\quad M=\frac{2B}{\mu_0}$$

M – the magnetization of the magnet
$B_m$ - magnetic flux density of the magnet, T
$x_1$ - distance between the magnets, m
$h_1$ - length (the height of the magnet), m.

Magnet’s magnetization M is proportional to the magnetic flux density B, the proportionality factor being the air permeability.
This simplified expression of the magnet-magnet interaction force will be used to calculate the attraction force of the magnets arranged corresponding to Fig. 4.
In order to analyze the solenoid-magnet interaction without losing generality, we can use the same simplified relation if the core of the solenoid has the same diameter as the magnet diameter, and its length is considered the length of the coiled zone ($h_2$).
Interaction force solenoid-magnet is described by expression:

$$F(x_2)=\frac{\pi\cdot B_m\cdot N\cdot I}{4\cdot h_2}r^4\ p_2 \tag{6}$$

$$p_2=\left[\frac{1}{x_2^{\ 2}}+\frac{1}{(x_2+h_1+h_2)^2}-\frac{2}{\left(x_{21}+\frac{h_1+h_2}{2}\right)^2}\right]$$

where:
$B_s=\frac{\mu_0NI}{h_2}$ the solenoid’s induction in air
$h_2$ – the coil length (solenoid equivalent height)
$h_1$ – the permanent magnet height
$x_2$ – the distance solenoid-magnet.

## 3. THE MODELING OF ELECTROMAGNETIC ACTUATION

Mathematical modeling of the actuation is based on estimation of dependence between the current I through solenoid and the displacement of arm at the element effector level and is based on the following simplifying assumptions:
a). The arm is a beam whose deformation is considered to be perfectly linear (the strain in the application of electromagnetic force zone is directly proportional to the strain in the element effector zone);
b). The deflection of the arm under the action of the bending force F is achieved by the integration of the bending moment. In case of a concentrated force, the beam deformation in application point of the force is dependent on this force by relation:

$$w=\frac{F\cdot l^3}{3\cdot I_zE} \tag{7}$$

w - the beam deflection at the force application point (magnet zone)
l – lengt of the beam
$I_z$ - beam inertia moment
E - the elastic modulus of the material (CoCrMo obtained by selective laser sintering technology).
c). Because the magnet-magnet interaction has as results an equal bending to both arms of the actuator, we use in modeling the assumption that magnet-magnet interaction force has a complete effect on the beam bending. Under these conditions, the total force which produces the bending of a single arm will be:

$$F = F_{mm} + F_{sm} = F_{(x_1)} + F_{(x_2)} \tag{8}$$

$$F = w\frac{3 \cdot I_z E}{l^3} = \frac{\frac{\pi B_m^2}{4\mu_0} r^4 p_1}{2} + \frac{\pi \cdot B_m \cdot N \cdot I}{4 \cdot h_2} r^4\ p_2 \tag{9}$$

$$\frac{\pi \cdot B_m \cdot N \cdot I}{4 \cdot h_2} r^4\ p_2 = w\frac{3 \cdot I_z E}{l^3} - \frac{\pi B_m^2}{8\mu_0} r^4 p_1 \tag{10}$$

From equations (9) and (10) it can be deduced the value of current through coil in order to create a necessary force which has as effect a displacement w.

$$I = w\frac{12 h_2 E I_z}{\pi B_m N r^4 l^3 p_2} - \frac{h_2 B_m}{2N\mu_0} \cdot \frac{p_1}{p_2} \tag{11}$$

It can be observed the linear dependence between the dependent variable *I* and independent variable *w* (11).

## 4. THE TESTING AND CHARACTERIZATION OF ELECTROMAGNETIC ACTUATION. RESULTS AND DISCUSSIONS

The elastic characteristics of the manipulator arm were estimated by a bending test of a specimen with a testing machine that allowed the monitoring of the force values, respectively, of the displacement [6] by using a data acquisition card.

The values of the force which can be captured by the machine are large enough to produce strain that exceed the deformations of micromanipulator arms, the force-displacement curve can not be used as a references data for simulation of the actuator, but can by used for estimation of the material elastic modulus.

The appropriate representation of data (the force vs. expression $\frac{3 \cdot w \cdot I_z}{l^3}$, according to equation (7)) it can be used for longitudinal elastic modulus estimation, as it can be seen in Figure 5 (E = 120160MPa).

The simulation of the dependence between the value of current I used for actuation of the arm and its displacement w, by using the relation (11) is illustrated in Figure 6. The curve 1 is characteristic for the deformation of the manipulator arm at the force application point (the fixing zone of the permanent magnet), and the curve 2 represents the displacement at the end-effector level.

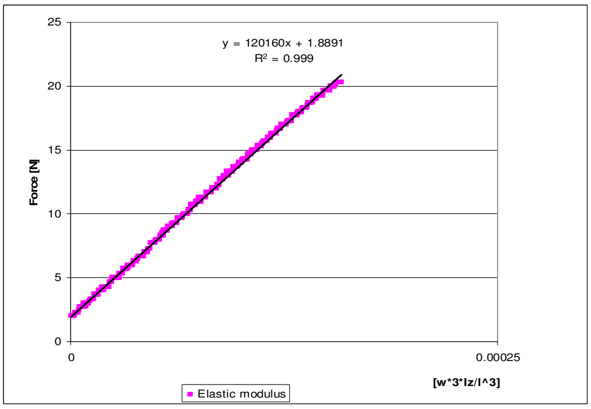


**Fig.5. The estimation of the longitudinal elastic modulus**

Regarding the current sense through the solenoid, because of the fact that the results may seem confusing, some clarifications are needed. The estimated deformations shown in Figure 6 are measured according to the position *"0 abs"* from Figure 4.

When permanent magnets are fixed on the micromanipulator arms, the attraction force of these ones has as effect the bending of arms and a displacement in position *"0 rel"*. For decrease the distance between arms, it is necessary an extra force which can be provide by increasing values of current through solenoid.

In case of moving away from the position *"0 rel"* (close to *"0 abs"*), it is necessary a changing of current sense in order to compensate the initial interaction between the permanent magnets.

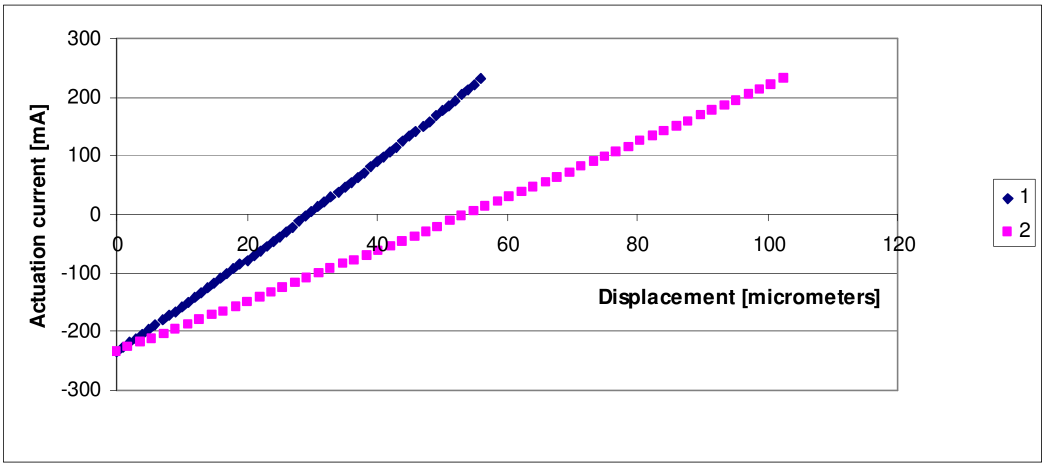


**Fig.6. Deformation at the application point of the force and end effector according to the current through the solenoid**

In order to validate the considered mathematical model, there were necessary experimental determinations of the micro-manipulator displacement involving the use of a submicrometric precision displacement sensor [7].
Thus, we used a laser triangulation measuring system, model Keyence LK-G3001PV. The system selected for a measuring range of ± 1mm, has a 0,1% linearity, a 0,05 µm repeatability and range of sampling rate adjustable between 20 ÷ 1000 µs.
The sensor contains a class II laser, 0,95 mW at the wave length 655 nm, which is characteristic of red color from the light spectrum (Fig. 7).

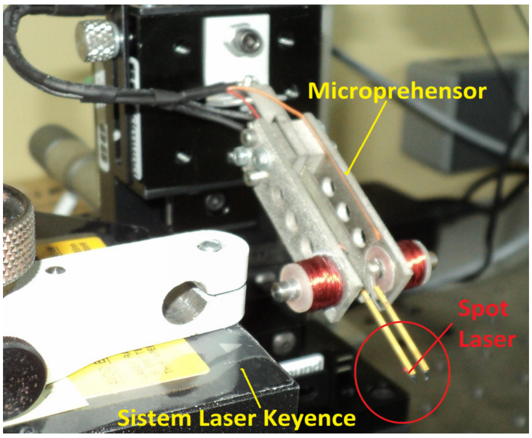


**Fig.7. The experimental setup for electromagnetic actuation of the device arms**

The system allows a local measurement, the spot being focused on a measuring surface with 30 µm diameter.
Because the measurement of displacement was performed at end-effector level, the equilibrium being considered characteristic for the position *"0 rel"*, the values from the simulated version have been corrected by a constant whose value is the displacement according to the position *"0 rel"* (current through solenoid is zero).

In Figure 8 are shown the results of the device simulation (the correlation between the current in the solenoid and the arm displacement at the level of the force application point (1), respectively, at the level of the end-effector (2).

The differences between the simulated curve at the end-effector level and the experimental one could be inaccuracie in estimation of magnetic induction value, uniformity of magnetic field, errors in assumption that a coil can be considered a permanent magnet with the same magnetisation.

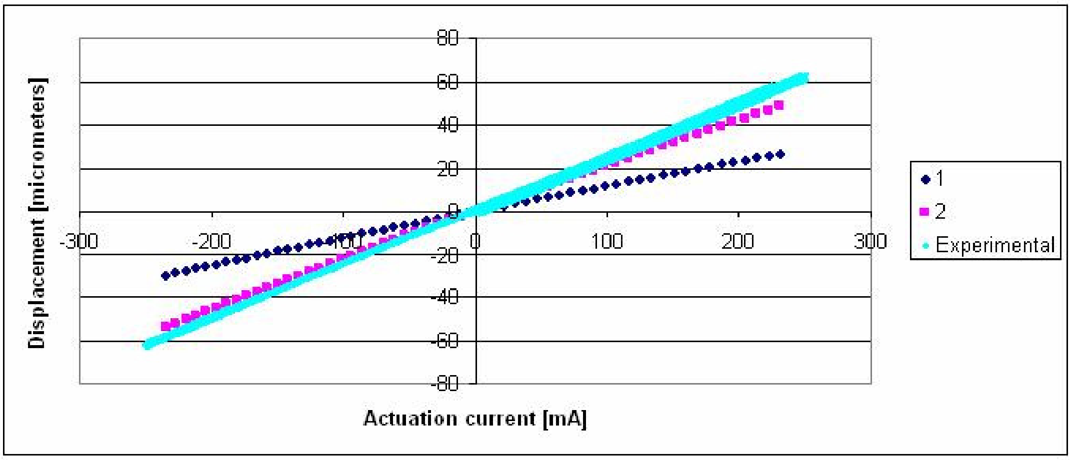


**Fig.8. A comparison between the current displacement simulated characteristic and the experimental characteristic**

## 4. CONCLUSIONS:

1. The tests performed on each arm of the manipulator shown a narrow hysteresis loop ($\varepsilon_{max}$=1,5%), as well as a good linearity ($\varepsilon_{lin\ max}$=1,8%).
2. For an intensity I = ± 250 mA, there is a displacement w=120µm/arm, which corresponds to an actuation coefficient of about 0,2 µm/mA. In microprehensor configuration, the maximum distance between the arms is double, d = 240 µm, enough for manipulation of objects with micrometer size (smaller than 100µm, in this case).
3. There is a good correlation between the data of the simulated curve and the data from the experimental one.

**ACKNOWLEDGEMENT**

National Project, Young Research Teams, PN-II-RU-TE-2011-3-0299, no. 85/05.10.2011, *“Advanced Devices for Micro and Nanoscale Manipulation and Characterization (ADMAN)“.*

**REFERENCES:**

[1]. Vorohobov V., *Interaction of cylindrical magnet with semi-space,* Magnetohydrodynamics Vol. 46 (2010), No.2, pp. 3–13.

[2]. Robertson W., Cazzolato B., Zander A., *Axial force between a thick coil and a cylindrical permanent magnet: optimising the geometry of an electromagnetic actuator,* IEEE Transaction on Magnetics, ISSN 0018-9464 (Vol. 48, Issue 9), 2012, pp. 2479-2487.

[3]. Furlani E.P., *Permanent magnet and electromechanical devices*, I. Mayegoyz, Ed. Academic Press, 2001.

[4]. Vokoun D., Beleggia M., Heller L., Šittner P. *Magnetostatic interactions and forces between cylindrical permanent magnets*, Journal of Magnetism and Magnetic Materials, Vol. 321, Issue 22, November 2009, pp. 3758–3763.

[5]. Babic S., Akyel C., *Magnetic force between magnetic disks,* IEEE Transaction on Magnetics, Vol.44, No.4, pp.445-452, April 2008.

[6]. Despa V., Catangiu A., Ivan I.A., *Mechanical behaviour of CoCrMo alloy samples made by selective laser sintering,* The Scientific Bulletin of Valahia University – Materials and Mechanics, Year 11, No.8 (11), ISSN 1844–1076, pag. 29-32.

[7]. Gheorghe Gh., Simona I., Despa V. Cirstoiu A**.**, *Researchs regarding intelligent sensors and actuators of high precision used in precision Mechanics, Mechatronics and Robotics domain*, *The Romanian Review Precision Mechanics, Optics & Mechatronics*, No.38 (2010), pp. 201-204.