# MMAB 2007

13th IEEE/IFAC International Conference on

# Methods and Models in Automation and Robotics

## ABSTRACTS

27–30 August 2007
Szczecin, Poland

IFAC IEEE

IEEE Robotics & Automation Society

IEEE Control Systems Society

# Pneumatic Fuzzy Controller for a Flexible Arm

J. M. Ramos, E. Gorrostieta, *Member, IEEE*, E. Vargas, J. C. Pedraza, R. J. Romero y B. Ramírez

*Abstract*— **This work shows the development of a pneumatic cylinder fuzzy controller that due to compressibility air characteristics presents a highly non linear behavior. The control is carried out considering only the rod displacement relative to the cylinder, who gives the force to move the flexible arm. A Fuzzy-PID comparison is also shown. The presented research is part of a Flexible Manipulator Robot -with one degree of freedom and dielectric characteristics- for porcelain isolator cleaning of high voltage transmission lines. A simplified Thermo-Mechanical model has been developed for manipulator control simulation. This paper shows a control proposal alternative, trough the application of Fuzzy Logic algorithms.**

## I. Introduction

THE pneumatic position control is a problem with high non linearity due to the air compressibility. The idea of developing a flexible manipulator robot with pneumatic actuator, comes from the necessity of cleaning the porcelain isolator on high voltage transmission lines [1], without a human risk.

As a matter of fact, most of manipulators robots use electric or hydraulic actuators, however the pneumatic actuators are being used in a recent years [2] [3] to control a flexible manipulator arm. This work is a continuation of the conjunction (?) of flexible manipulators and electro-pneumatic control.

This is the beginning of a project which involves the use of a pneumatic cylinder to control a flexible manipulator robot. Our first approach is to use one degree of freedom, but the main goal is to have a two degree of freedom flexible manipulator.

Pneumatic cylinders are very useful for its clean, economy and low weight; however, due to air compressibility and internal friction, they present a highly non linear behavior [4]. Because of these conditions, there are certain difficulties in pneumatics cylinder control design.

Several pneumatic controllers had been developed; for example, the Model Reference Adaptive Control, MRAC [5]; however, the pneumatic model used for the control design, have the next considerations; a lineal actuator, a lineal valve, without damping systems at the sides, ideal gas, adiabatic changes and constant viscous friction.

Other works have been focused in friction parameter identification techniques of cylinder pneumatic [6], dynamic modeling and simulation [7], analytic and experimental research [8] and the development of robotic hands using cylinder pneumatics.

Flexible manipulators are light, cheap and have a higher power-weight relation robot. This type of robot can be used only under two conditions; a) when the robot weight must be minimized, and b) when the collisions in the work space needs to be avoided [9]. The modeling of flexible manipulators have been developed almost 35 years ago [10] [11], where, almost in all cases, they used electric or hydraulic actuators, and pneumatic cylinders are discouraged due to their non linear behavior.

Pneumatic control started in 1968 with Burrows [12], and recent works are focused mainly with adaptive control methods [5] [13], some of them use a computer to implement the control [14]. Other researchs are focused on mechanical system modeling using a pneumatic actuators [15], from these kind of works, a Flexible Manipulator Model with pneumatic cylinder -called Thermo-Mechanical model- was developed, then the mechanical system is involved to give the movement for the flexible arm [16].

By other hand [17], electric actuators are used in the development of flexible manipulators, where the motor speed is considered for the control implementation along with the motor effects and the mechanical structure.

In our system we are using a flexible manipulator robot with a pneumatic actuator, where we consider the damping systems in both sides and the mechanical dynamics for control. The full Thermo-Mechanical model [16] is used as a starting point, later it is simplified and the results are used for the control development. One contribution of this work is the position control of a flexible manipulator using a pneumatic actuator and a simplified Thermo-Mechanical model.

The integral Thermo-Mechanical model of pneumatic actuators allows us to predict its behavior, considering the air compressibility effects, internal friction forces, damping

Manuscript received April 2nd, 2007. This work was supported by CONACYT and Universidad Tecnológica de San Juan del Río.

J. M. Ramos is a researcher and lecturer at Universidad Tecnológica de San Juan del Río, Querétaro, Qro., 76800 México; phone: 427-272-8448; fax: 427-272-8449; e-mail: jmramosa@utsjr.edu.mx

E. Gorrostieta is a researcher and lecturer at Instituto Tecnológico de Querétaro; Querétaro, QRO., 76000 México; e-mail: efren.hurtado@usa.net

E. Vargas is a researcher at Universidad Anáhuac del Sur, México, D. F. 01780 México; e-mail: emiliov@ds.uas.mx

J. C. Pedraza is a researcher and lecturer at Centro de Ingeniería y Desarrollo Industrial, Querétaro, Qro., 76130 México; e-mail: jpedraza@cidesi.mx

R. J. Romero is a researcher at Facultad de Ingeniería Mecánica, Eléctrica y Electrónica, Universidad de Guanajuato, Salamanca, Gto., 36730 México; e-mail: troncoso@salamanca.ugto.mx

B. Ramírez is a lecturer at Universidad Tecnológica de San Juan del Río, Querétaro, Qro., 76800 México; e-mail: bernardorp@utsjr.edu.mx

effects in both extremes of the cylinder, massic flow and energy conservation; and gives us the instant pressure, that depends on the rod position.

From the engineering control point of view, this model let us predict the variable behavior, involved in the physical process, and can be used for control purposes.

This paper talks about a Fuzzy Logic simulation to control the rod displacement of a flexible manipulator arm. It generates a force used to get an angular movement for the arm. At this moment, the flexible behavior of the arm, is not considered.

## II. The Pneumatic System

The complete system is showed in figure 1, and we call the PLANT. The output plant is $\theta_6$, corresponding to the arm elevation. The arm movement depends of the rod displacement and the cylinder force generated by the air pressure and the valve position, according with the figure 2.

The 5/2 electro valve is used to control the rod direction, using two proportional valves, represented by $A_1$ and $A_3$.

The system of the figure 2 has a mathematical model, and is called Simplified Thermo-Mechanical Model [1]. This model is divided in several intervals as shown in the eqs. (1) to (10).

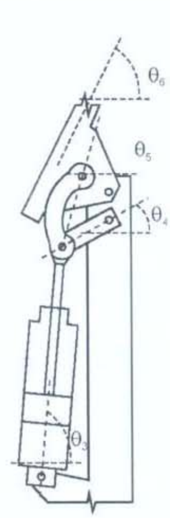


Fig. 1. Mechanical-Pneumatic system for the flexible manipulator.

The Thermo-Mechanical controller developed previously [2] includes a PID, discrete PID and a speed change feedback proposals. In this works a fuzzy control is proposed, considering the pneumatic system as shown in figure 2.

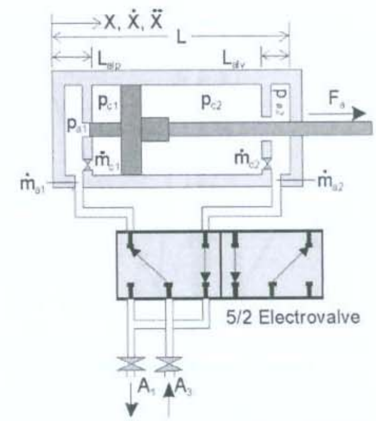


Fig. 2. Pneumatic system for the flexible arm manipulator.

For the interval $0 \le X \le L$:

$$\dot{X} = \frac{d}{dt}X \tag{1}$$

$$D\dot{X} = \frac{d^2}{dt^2}X \tag{2}$$

For the interval $0 \le X \le L_{alp}$

$$\dot{P}_{a1} = g_{21}(X)\left(\dot{m}_{a1} - \dot{m}_{c1} - 9.176\times10^{-10}P_{a1}DX\right)\times10^{8} \tag{3}$$

$$\dot{P}_{c1} = g_{31}(X)\left(\dot{m}_{c1} - 3.608\times10^{-8}P_{c1}DX\right)\times10^{6} \tag{4}$$

For the interval $L_{alp} < X \le L$

$$\dot{P}_{a1} = g_{22}(X)\left(\dot{m}_{a1} - 3.7\times10^{-8}P_{a1}DX\right)\times10^{11} \tag{5}$$

$$\dot{P}_{c1} = g_{32}(X)\left(\dot{m}_{c1} - 3.7\times10^{-8}P_{c1}DX\right)\times10^{11} \tag{6}$$

For the interval $0 \le X \le (L-L_{alv})$

$$\dot{P}_{c2} = g_{41}(X)\left(\dot{m}_{c2} + 3.469\times10^{-8}P_{c2}DX\right)\times10^{11} \tag{7}$$

$$\dot{P}_{a2} = g_{51}(X)\left(\dot{m}_{a2} + 3.469\times10^{-8}P_{a2}DX\right)\times10^{11} \tag{8}$$

For the interval $(L - L_{alv}) < X \le L$

$$\dot{P}_{c2} = g_{42}(X)\left(\dot{m}_{c2} + 3.352\times10^{-8}X_4X_6\right)\times10^{13} \tag{9}$$

$$\dot{P}_{a2} = g_{52}(X)\begin{bmatrix}9.983\times10^{3}(\dot{m}_{a2} - \dot{m}_{c2}) + \\ 1.168\times10^{-5}X_5X_6\end{bmatrix}\times10^{4} \tag{10}$$

## III. Fuzzy Controller

The Thermo-Mechanical Model has the next control inputs: the valve effective area air flow, eq. (11).

$$u = [A_1, A_2, A_3] \tag{11}$$

where $A_1$, $A_2$ and $A_3$ are the valve area of cylinder side, rod side, and air return, respectively. However the value of $A_1$ and $A_2$ are the same.

### *A. The Fuzzy Controller Proposal*

Figure 3 shows the control block diagram used for the pneumatic actuator system, taking the θ angle as the mechanical system output.

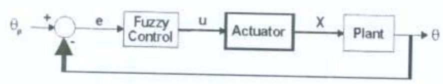


Fig. 2. Position Controller of manipulator arm with pneumatic actuator.

Equation (12), shows the error equation; the eqs. (13) and (14) shows the proportional valve open level, obtained with a fuzzy logic method, where $\theta_p$ is the reference and θ is the actual position of the arm.

$$e = \theta_p - \theta \tag{12}$$

$$[A_1, A_3] = fuzzy(\theta_p, \theta, e) \tag{13}$$

$$A_2 = A_1 \tag{14}$$

Next, the fuzzy rules used to solve the problem.

### *B. The Fuzzy rules*

Before the rule settings, both inputs and outputs variables were specified, and are showed in table 1.

TABLE I
FUZZY RULES, INPUTS AND OUTPUS.

| Input | Output |
|---|---|
| Reference, $\theta_p$ | Valve 1, $A_1$ |
| Angle, θ | Valve 2, $A_3$ |
| Error, *e* | |

The membership functions used in the fuzzy process are showed in figures 3 to 7. The used membership functions for the input variables, called reference and angle are the same; and the membership functions for the output variables called valve open $A_1$ and $A_2$, are the same.

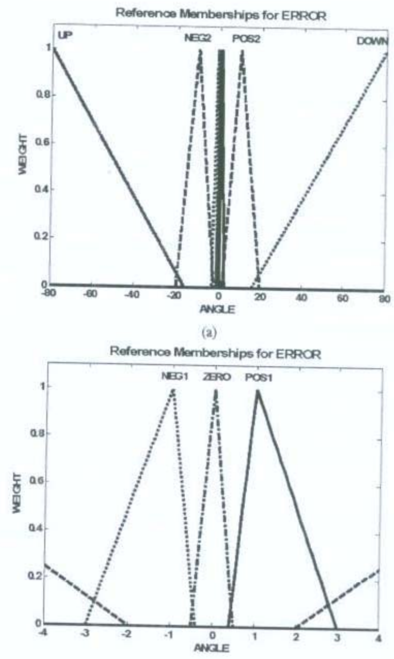


Fig. 3. Memberships for ERROR input. (a) The external part. (b) The internal interval.

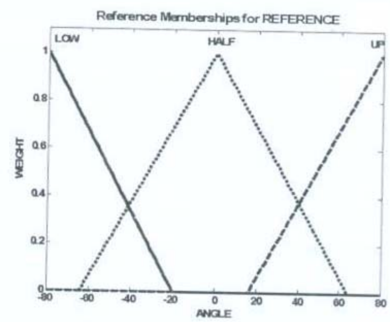


Fig. 4. Memberships for REFERENCE input.

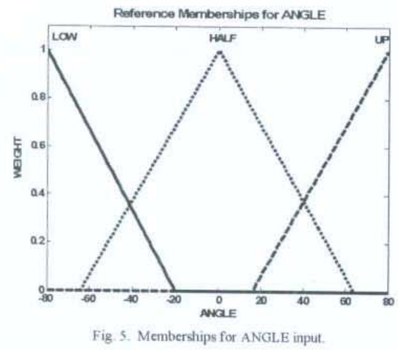


Fig. 5. Memberships for ANGLE input.

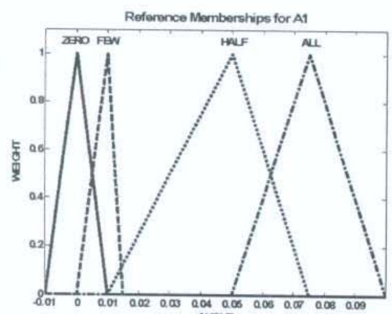


Fig. 6. Memberships for the valve 1.

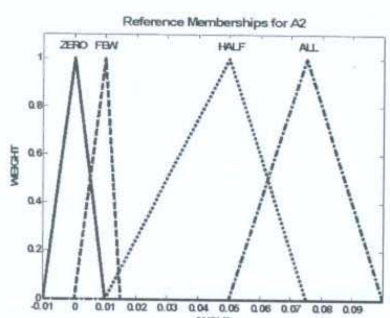


Fig. 7. Memberships for the valve 2.

These membership functions are used to control the pneumatic actuator on the manipulator system. Next, the fuzzy rules are used to control the plant.

### C. *Fuzzy Rules*

In the fuzzy process, the control needs 26 rules, and those rules are distributed depending of the interval of each variable, as can be seen on tables 2, 3 and 4. The triangular membership function is used in this process. Tables 2, 3, and 4 show the triangular memberships break points used for the input and output variables. Table 5 shows the rules used to control the pneumatic actuator behavior, which is responsible of getting a desired arm position.

The values for $A_1$ and $A_3$ are normalized, that is, a value of 1.0 represents a 100% open valve (completely open); a 0.5 represents a 50% open valve and 0% means the valve is completely closed.

TABLE II

BREAK POINTS OF TRIANGULAR MEMBERSHIPS USED FOR REFERENCE AND ANGLE INPUTS VARIABLES.

| Interval of Reference and Angle: $-80° \leq \theta_p \leq 80°$ | |
|---|---|
| Membership | Triangular break points |
| LOW | [-144 -80 -20] |
| HALF | [-64 0 64] |
| UP | [16 80 144] |

TABLE III

BREAK POINTS OF TRIANGULAR MEMBERSHIPS USED FOR ERROR INPUT VARIABLES.

| Interval of Error: $-80° \leq \theta_p \leq 80°$ | |
|---|---|
| Membership | Triangular break points |
| UP | [-144 -80 -16] |
| NEG2 | [-20 -10 -2] |
| NEG1 | [-3 -1 -0.4] |
| ZERO | [-0.5 0 0.5] |
| POS1 | [0.4 1 3] |
| POS2 | [2 10 20] |
| DOWN | [16 80 144] |

TABLE IV

BREAK POINTS OF TRIANGULAR MEMBERSHIPS USED FOR $A_1$ AND $A_3$ INPUT VARIABLES.

| Interval of $A_1$ and $A_2$: $0.0 \leq \theta_p \leq 0.1$ | |
|---|---|
| Membership | Triangular break points |
| ZERO | [-0.01 0.000 0.010] |
| FEW | [ 0.00 0.010 0.015] |
| HALF | [ 0.01 0.050 0.075] |
| ALL | [ 0.05 0.075 0.100] |

The fuzzy rules are organized in a table to easy the review. The *inputs* and *outputs* variables are in different columns, and the relationship between each input and output was done by a simulation, using Matlab and its fuzzy logic toolbox. In this proposal, a fuzzy algorithm is implemented in simple way. The results are compared with a combination of fuzzy and PID control, called Fuzzy-PID.

TABLE V
SET OF FUZZY RULES USED IN THE CONTROL PROCESS.

| INPUT | | | OUTPUT | |
|---|---|---|---|---|
| Reference | Angle | Error | $A_1$ | $A_2$ |
| LOW | LOW | NEG2 | FEW | FEW |
| LOW | LOW | NEG1 | FEW | ZERO |
| LOW | LOW | ZERO | ZERO | ZERO |
| LOW | LOW | ZERO | ZERO | ZERO |
| LOW | LOW | POS1 | FEW | ZERO |
| LOW | LOW | POS2 | FEW | FEW |
| LOW | HALF | DOWN | HALF | FEW |
| LOW | UP | DOWN | ALL | HALF |
| HALF | LOW | UP | HALF | FEW |
| HALF | HALF | UP | FEW | FEW |
| HALF | HALF | NEG2 | FEW | FEW |
| HALF | HALF | NEG1 | FEW | ZERO |
| HALF | HALF | ZERO | ZERO | ZERO |
| HALF | HALF | POS1 | FEW | FEW |
| HALF | HALF | POS2 | FEW | FEW |
| HALF | HALF | DOWN | HALF | FEW |
| HALF | UP | DOWN | HALF | HALF |
| UP | UP | UP | FEW | FEW |
| UP | UP | NEG1 | FEW | ZERO |
| UP | UP | NEG2 | FEW | FEW |
| UP | UP | ZERO | ZERO | ZERO |
| UP | UP | POS1 | FEW | ZERO |
| UP | UP | POS2 | FEW | FEW |
| UP | HALF | UP | HALF | HALF |
| UP | LOW | UP | HALF | HALF |

The behavior obtained is compared with a PID control, where the parameters values for $K_p$, $K_d$ and $K_i$, are determinate by a fuzzy logic process, called Fuzzy-PID, as shows in figure 8.

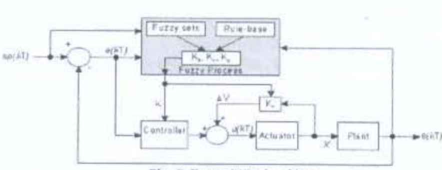


Fig. 8. Fuzzy-PID algorithm.

## IV. RESULTS

To test the behavior of the system, a set points vector was used, as shows the eq. (15).

$$\theta_p = \{61, 12, -72, 25, 79\} \qquad (15)$$

Figure 9 shows the fuzzy control results. Figures 10 and 11 are showing the valves behavior. The values for open valve are small, due to the air pressure; if the valve open are high, the actuator goes up too fast and arrive to the top in less than one second; in simulation way, the maximum value for the valves was established in 10%.

This result was compared with a Fuzzy-PID algorithm control, to establish the difference between both controls. The figure 12 shows the result of comparison.

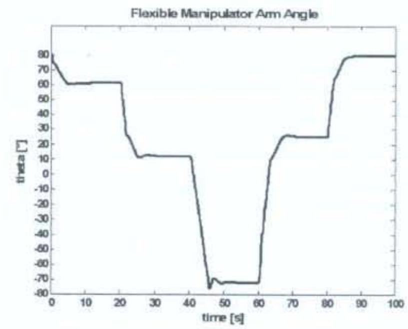


Fig. 9. Flexible arm angle behavior using a fuzzy control.

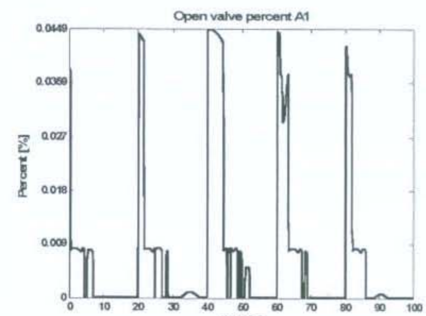


Fig. 10. Valve $A_1$ behavior.

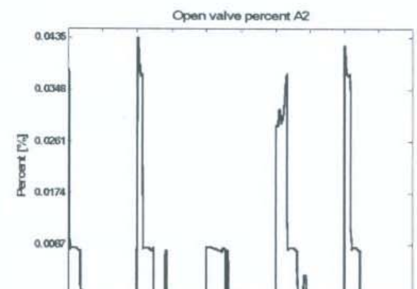


Fig. 11. Valve $A_2$ behavior.

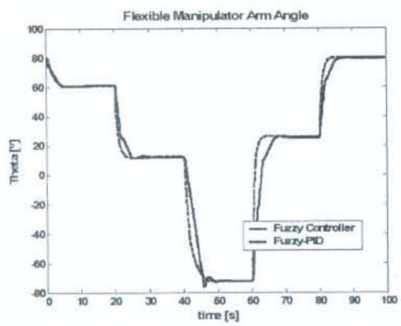


Fig. 12. A comparison between fuzzy control and fuzzy-PID control behavior.

## V. Conclusions

The pneumatic actuator is used to generate a flexible manipulator arm displacement in radial way. To control the air flow through the cylinder, a fuzzy logic algorithm was implemented.

This works present a Fuzzy Logic control, where a pneumatic actuator must be controlled. The pneumatic cylinder has to generate the force to move the flexible arm. We are working only with pneumatic part; the flexible behavior is part of future work.

The Fuzzy control works only with the percent of valve open, to limit the air flow from the compressor trough the cylinder chambers. The values for $A_1$ and $A_2$ are the same, but different for $A_3$. Actually $A_3$ must be small than $A_1$ to get a better system response. In this case, we can see that a single Fuzzy Logic control is not enough to get a soft behavior of the system, and a PID algorithm must be used.

As future work, is considering the use of reference frame, neuronal networks and maybe a combination of those controllers.

## References

[1] Juan M. Ramos, José E. Vargas, Efren Gorrostieta y Jesus C. Pedraza; Nuevo Modelo Polinomial del Comportamiento de un Cilindro Neumatico; Revista Internacional Informacion Tecnologica; vol. 17, no. 3; ISSN 0716-8756; 2006.

[2] J. M. Ramos, E. Gorrostieta, E. Vargas, J. C. Pedraza, R. J. Romero and B. Piñeiro; Pneumatic cylinder control for a flexible manipulator robot; 12th IEEE Internacional Conference on Methods and Model in Automation and Robotics, 28 – 31 August 2006, Miedzyzdroje, Poland; ISBN 978-83-60140-88-8.

[3] J. M. Ramos, E. Vargas, E. Gorrostieta, R. J. Romero, J. C. Pedraza; Pneumatic Cylinder Control PID for Manipulator Robot; 2006 International Conference on Dynamics, Instrumentation and Control; Queretaro, México, August 13-16 2006.

[4] Moore P. y J. Pu; Progression of servo pneumatics toward advanced applications; Fluid Power Circuit, Component and System Design; K. Edge and C. Burrows, Eds. Boldock, U. K.: Research Studies Press; páginas 347 a 365; 1993.

[5] Suarez L. y S. Luis; Estrategias de Control Adaptable para el posicionamiento continuo de Cilindros Neumáticos; XI Convención Informática 2005; La Habana, Cuba; ISBN 959-7164-87-6; 2005.

[6] Wang J. y J. D. Wang; Identification of Pneumatic Cylinder Friction Parameters using Genetic Algorithms; IEEE Transactions on Mechatronics; vol. 9, no. 1; pages 100 to 107; 2004.

[7] Jozsef K. y J. Claude; Dynamics Modeling and Simulation of Constrained Robotic System; IEEE/ASME Transactions on Mechatronics; vol. 8, no. 2; pages 165 to 177; 2003.

[8] Henri P., J. M. Hollerbach; An Analytical and Experimental Invetigation of a Jet Pipe controlled electropneumatic Actuator; IEEE Transactions on Robotics and Automation; vol. 14, no. 4; pages 601 to 611; 1998.

[9] V. Feliu, A. Garcia, J.A. Somolinos; Gauge-Based Tip Position Control of a New Three –Degree-Freedom Flexible Robot; The International Journal of Robotics Research; vol. 20, no. 8; pp. 660-675; August 2001.

[10] Mirro, John; Automatic Feedback Control of a Vibrating Flexible Beam; MS Thesis, Department of Mechanical Engineering, Massachussets Institute of Technology, August 1972.

[11] Whitney, D. E., Book, W. J. And Lynch, P. M.; Design and Control Considerations for Industrial and Space Manipulators; Proceedings of the Joint Automatic Control Conference, June, 1974.

[12] Burrows C.R., Webb C.R.; Simulation of an On – Off Pneumatic Servomechanism; Automatic Control Group, 1968.

[13] E. Quiles, F. Morant, E. García, R. Blasco, A. Correcher; Control Adaptivo de un Sistema de Control Neumatico; 3ra. Conferencia Iberoamericana en Sistemas, Cibernetica e Informatica CISCI, Julio 2004.

[14] Juan Carlos Burbano Jaramillo, Germán A. Bacca Bastidas, Mario Hoyos Mesa; Control de Posicion y Presion para Manipulador Neumatico a traves de PC; Scientia Et Tecnica, UTP; vol. 21, pp. 71-76; 2003.

[15] Joaquin Pérez Meneses; Analisis Dinamico de Mecanismos Accionados Neumaticamente; Ph.D. Thesis; Facultad de Ingenieria Mecanica, Electrica y Electronica, FIMEE; Salamanca, Gto.; March 2003.

[16] Kiyama F. y J. E. Vargas; Modelo Termo-Mecanico para un Manipulador tipo Dielectrico; Informacion Tecnologica; vol. 15; no 5; pages 23 to 31; 2004; ISSN 0716-8756.

[17] Feliu V. y A. Garcia; Gauge-Based tip Position Control of a New Three Degree of Freedom Flexible Robot; The International Journal of Robotics Research; vol. 20, no. 8; pp. 660-675; 2001.

**MEDIA SPONSORSHIP**

CONTROL ENGINEERING Polska

Institute of Control Engineering
Szczecin University of Technology

ISBN 978-83-751803-2-9