Conventional Control and Fuzzy Control Algorithms for Shape Memory Alloy based Tendons Robotic Structure

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Abstract: - Shape memory alloy offer an interesting solution, using the shape transformation of the wire/structure in the moment of applying a thermal type transformation able to offer the martensitic temperature. This thermal transformation can be inducted using electrical current and a suitable control strategy. In order to assure an efficient control of robotics SMA actuator, a mathematical model and numerical simulation of the resulting model is required. For an efficient study a Simulink block is developed (block for user configurable shape memory alloy material). Due a particular possibility SMA actuator connection, a modified dynamics for wire or tendon actuation is presented. The control possibilities are explored: PI, PD,PID and fuzzy logic controller are connected to the single link SMA actuation. Experimental results and numerical simulations are presented and observations are formulated.

Key-Words: - smart materials, shape memory alloy, robotics, conventional control, fuzzy logic, numerical simulation

1 Introduction

The shape memory effect was first noted over 50 years ago; it was not until 1962, however, with the discovery of a nickel titanium shape memory alloy but Buehler, that serious investigations were undertaken to understand the mechanism of the shape memory effect. The shape memory alloys possess the ability to undergo shape change at low temperature and retain this deformation until they are heated, at which point they return to their original shape. The nickel titanium alloys, used in the present research, generally refereed to as Nitinol, have compositions of approximately 50 atomic % Ni/ 50 atomic % Ti, with small additions of copper, iron, cobalt or chromium. The alloys are four times the cost of Cu-Zn-Al alloys, but it possesses several advantages as greater ductility, more recoverable motion, excellent corrosion resistance, stable transformation temperatures, high biocompatibility and the ability to be electrically heated for shape recovery [1].

Shape memory actuators are considered to be low power actuators and such as compete with solenoids, bimetals and to some degree was motors. It is estimated that shape memory springs can provide over 100 times the work output of thermal bimetals.

The use of shape memory alloy can sometimes simplify a mechanism or device, reducing the overall number of parts, increasing reliability and therefore reducing associated quality costs. Because of its high rezistivity of 80 – 89 micro ohm-cm, nickel titanium can be self heated by passing an electrical current through it [2].

The basic rule for electrical actuation is that the temperature of complete transformation to martensite Mf, of the actuator, must be well above the maximum ambient temperature expected.

1.1 Fuzzy logic control

Fuzzy logic is a method of rule-based decision making used for expert systems and process control that emulates the rule-of-thumb thought process used by human beings. The basis of fuzzy logic is fuzzy set theory which was developed by Lotfi Zadeh in the 1960s [3].

Defining a fuzzy controller, process control can be implemented quickly and easily. Many such systems are difficult or impossible to model mathematically, which is required for the design of most traditional control algorithms. In addition, many processes that might or might not be modeled mathematically are too complex or nonlinear to be controlled with traditional strategies. However, if a control strategy can be described qualitatively by an expert, fuzzy logic can be used to define a controller that emulates the heuristic rule-of-thumb strategies of the expert. Therefore, fuzzy logic can be used to control a process that a human can control manually with expertise gained from experience [4]. The linguistic control rules that a human expert can describe in an intuitive and general manner can be directly translated to a rule base for a fuzzy logic controller [5].

A fuzzy controller is composed of the three calculation steps Fuzzification, Fuzzy Inference and Defuzzification. The control strategy [6] based on engineering experience with respect to a closed-loop control application is implemented by linguistic rules integrated in the rule base of the controller.

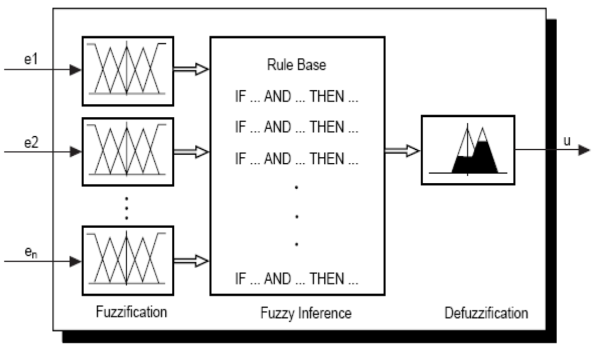

Fig.1 A fuzzy controller structure

Sliding mode control [7], [8] is a type of variable structure control where the dynamics of a nonlinear system is altered via application of a high-speed switching control. This is a state feedback control scheme where the feedback gains are not a continuous function of time. The control scheme involves following two steps:

- selection of a hypersurface or a manifold such that the system trajectory exhibits desirable behaviour when confined to this manifold.

- finding feed-back gains so that the system trajectory intersects and stays on the manifold.

The connection between these two controllers is more than appropriate:

- both use a rough approximated model of the plant

- both use a hard forced control

- both are nonlinear controllers.

The manifold border idea of sliding mode controller is related to human experience and expertise for nonlinear plants.

Forcing the outputs of controller to conduct the system error after o strait trajectory to zero connected with fuzzy approach reveal the Direct Sliding Mode Fuzzy Controller characteristics [9], [10]. Main disadvantages of this type of controller are the strong outputs dynamics and big value of outputs requirements.

1.2 Applications of shape memory alloy material in robotics

The alloys and manufacturing techniques improved, so did the experience and results of experimenters. Nitinol received much attention for medical applications, toys industry, teleoperated systems and robotics, especially autonomous robots.

In 1989 Oaktree Automation Inc, in Alexandria Virginia, started developing the Fingerspelling Hand, an anthropomorphic robotic device to serve as a tactile communication aid for deaf - blind individuals, particularly those unable to read Braille. The device used a total of one hundred and eight 250 μm Flexinol wires acting in parallel.

The most successful applications of shape memory alloy components usually have all or most of the following characteristics:

- A mechanically simple design
- The shape memory component pops in place and is held by other parts in the assembly
- The shape memory alloy component is in direct contact with a heating/cooling medium
- Friction is minimized and no complex stresses or stress concentrations are present
- A minimum force and motion requirement for the shape memory component
- The shape memory component is isolated from incidental forces with high variation
- The tolerances of all the components realistically interface with the shape memory component.

A more efficient support for robotics applications the SMA wires are SMA springs. The three basic modes in which a shape memory spring can be used are:

- constant force
- constant length
- simultaneous force and length variation.

Based on description of shape memory alloy materials, a SMA Simulink block was developed. The characteristic of material is idealized, but the approximations made are suitable for an efficient simulation. The user can indicate the start and stop martensitic and austenitic temperature and the force, momentum evolution.

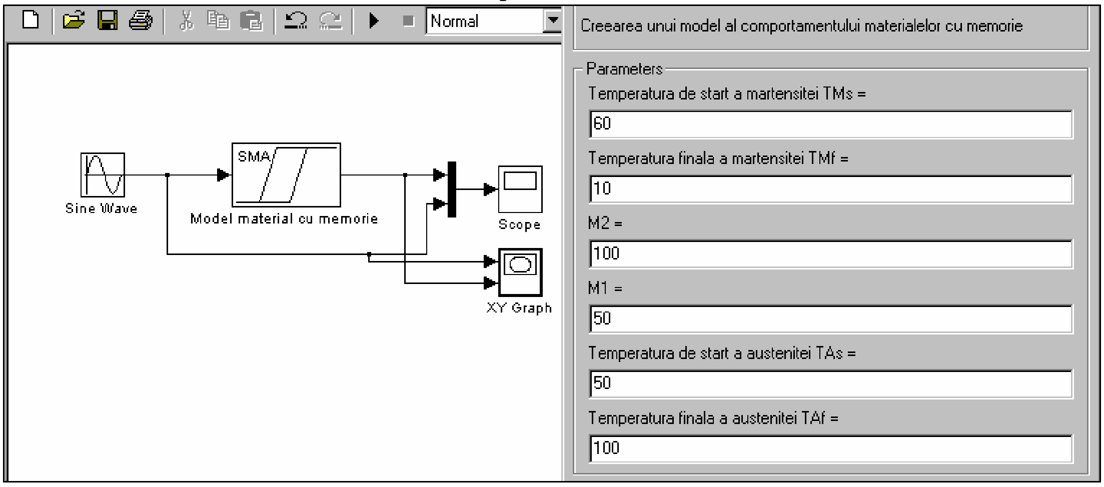

Fig.2 Shape memory alloy wire Simulink block

The numerical results respect the real comportment of the user specified shape memory alloy.

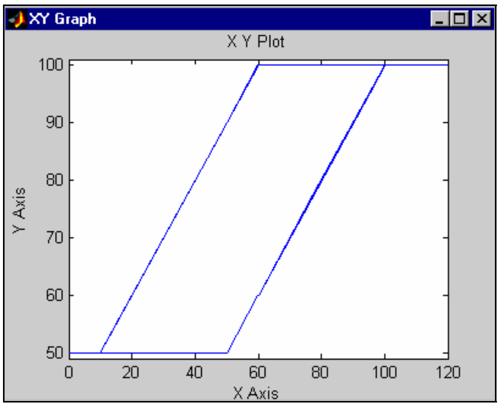

Fig.3 Temperature versus force numerical response of the SMA Simulink block

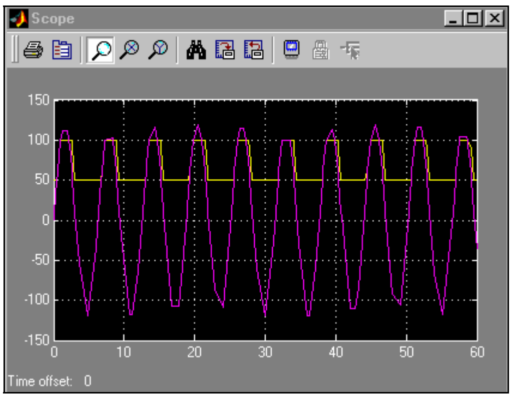

Fig.4 Temperature sinusoidal input numerical response for the SMA Simulink block

The electrical activation of SMA actuator imposes the following relations for the current, temperature and response time:

For heating

$$T_{Max} = 4{,}928\frac{I}{d} + 1{,}632\frac{I^2}{d^2} = K_{T1}\frac{I}{\sqrt{F_L}} + K_{T2}\frac{I^2}{F_L} \quad (1)$$

T_{Max} - maximum temperature,
d – wire diameter,
I – electrical current,
F_L - required force

$$t_{Heating} = J_h \ln\frac{T_{Max} - T_{medium}}{T_{Max} - T} \quad (2)$$

$t_{Heating}$ - heating time,
J_h - heating coefficient,
T_{medium} - medium temperature,
T_A - ambient temperature,
T - aim temperature upon heating

$$J_h = 6{,}72 + 3{,}922d^2 = K_{J_1} + K_{J_2}F_L \quad (3)$$

For cooling

$$t_c = J_c \ln\frac{T_H - T_A}{T_c - T_A} + \frac{28{,}88}{M_S - T_A} \quad (4)$$

$$J_c = 4{,}88 + 6{,}116d^2 = K_{J_{c1}} + K_{J_{c2}}F_L \quad (5)$$

t_c - cooling time,
T_H - initial temperature upon cooling,
T_A - ambient temperature,
d - wire diameter,
T_C - aim cooling temperature,
J_C - time constant for cooling,
M - martensitic start temperature.

One can observe the time dependence of required force and required stroke.

The electrical calculations for direct current heating determine:

- The amount of current needed for actuation in the required time
- The resistance of the nickel titanium actuation element
- The voltage required to drive the current through element
- The power dissipated by the actuation element.

The first requirement can be establish using the material description tables [14].

The resistance is determined using the following expression:

$$Resistance/mm = \frac{1{,}019x10^{-3}}{d^3}\Omega/mm \quad (6)$$

The voltage and power requirements results from:

$$V = IR\,;\ Power = I^2 R \quad (7)$$

I - current in amps,

V - voltage in volts, R resistance in Ω.

In case of using pulse width modulation heating the following relation can be used:

$$duty\ cycle(\%) = \frac{t_1}{t_2}x100 \quad (8)$$

t_1 - the width of constant current pulse,

t_2 - the total cycle time.

$$duty\ cycle(\%) = \frac{100}{I_i}\sqrt{\frac{P_{avr}}{R}} \quad (9)$$

$$duty\ cycle(\%) = \frac{100}{V_i}\sqrt{P_{avr}R} \quad (10)$$

P_{avg} – average pulsed power (effective DC power), I_i applied pulse current, V_i applied pulsed voltage, R electric resistance.

2 Dynamics Of Two-Link Tendon-Driven Robotic Structure

There are many methods for generating the dynamic equations of mechanical system [11], [12]. All methods generate equivalent sets of equations, but different forms of the equations may be better suited for computation different forms of the equations may be better suited for computation or analysis. The Lagrange analysis will be used for the present analysis, a method which relies on the energy proprieties of mechanical system to compute the equations of motion [13]. We consider that each link is a homogeneous rectangular bar with mass mi and moment of inertia tensor.

$$I_i = \begin{bmatrix} I_{xi} & 0 & 0 \\ 0 & I_{yi} & 0 \\ 0 & 0 & I_{zi} \end{bmatrix} \quad (11)$$

Letting $v_i \in R^3$ be the translational velocity of the centre of mass for the i[th] link and $\omega_i \in R^3$ be angular velocity, the kinetic energy of the manipulator is:

$$T(\theta,\dot{\theta}) = \frac{1}{2}m_1\|v_1\|^2 + \frac{1}{2}m_1\omega_1^T I_1\omega_1 + \frac{1}{2}m_1\|v_2\|^2 + \frac{1}{2}m_1\omega_2^T I_2\omega_2 \quad (12)$$

Since the motion of the manipulator is restricted to xy plane, $\|v_i\|$ is the magnitude of xy velocity of the centre of mass and ω_i is a vector in the direction of the y axis, with $\|\omega_1\| = \dot{\theta}_1$ and $\|\omega_2\| = \dot{\theta}_1 + \dot{\theta}_2$. We solve for kinetic energy in terms of the generalized coordinates by using the kinematics of the mechanism.

Using the kinetic energy and Lagrange methods results:

$$\begin{bmatrix} \alpha+\beta c_2 & \delta+\frac{1}{2}\beta c_2 \\ \delta+\frac{1}{2}\beta c_2 & \delta \end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix} + \begin{bmatrix} -\frac{1}{2}\beta s_2\dot{\theta}_2 & -\frac{1}{2}\beta s_2(\dot{\theta}_2+\dot{\theta}_1) \\ \frac{1}{2}\beta s_2\dot{\theta}_1 & 0 \end{bmatrix}\bullet\begin{bmatrix}\dot{\theta}_1\\ \dot{\theta}_2\end{bmatrix} = \begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} \quad (13)$$

where

$$\alpha = \frac{m_1}{12}\left(l_1^2 + w_1^2\right) + \frac{m_2}{12}\left(l_2^2 + w_2^2\right) + m_1 r_1^2 + m_2\left(l_1^2 + r_2^2\right) \quad (14)$$

$$\beta = m_2 l_1 l_2 \quad (15)$$

$$\delta = \frac{m_2}{12}\left(l_2^2 + w_2^2\right) + m_2 r_2^2 \quad (16)$$

with w_1, w_2, l_1, l_2 the width and respectively the length of link1 and link 2.

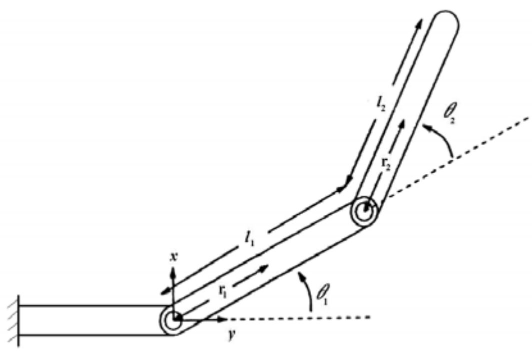

Fig.5 Two link robotic architecture

3 Problem Solution

Due the actuation architecture a simple mathematical model can be establish. Schematically the shape memory actuation is:

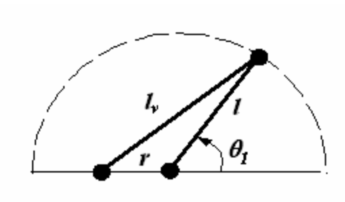

Fig.6 Shape memory alloy actuation structure

In Fig. 5 the l_v is the variable length of shape memory alloy wire, the l is the robotic link length between the articulation point and the shape memory alloy wire connection, r is the distance between the second end of the SMA wire (which is a fixed point) and the articulation point of the link (fixed point too).

Using simple mathematical computation the mathematical dependence can be established:

$$\theta_1 = \arccos\left(\frac{l_v^2 - \left(r^2 + l^2\right)}{2lr}\right) \Leftrightarrow \theta_1 = f\left(l_v^2\right) \qquad (17)$$

The graphic of θ_1 as function of l_v is the following, considering the real domain variation for $\theta_1 \in [0, \pi]$.

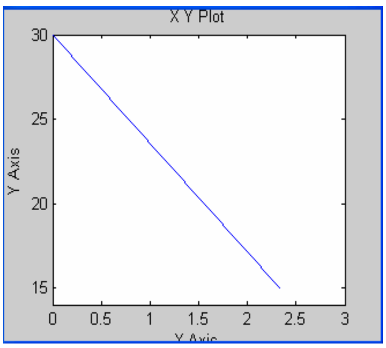

Fig.7 The graphic $l_v = f\left(\theta_1\right)$

As can easily see the dependence is linear, that the linearization in modelling can be done successfully. The explanations concern the structural variation of SMA actuator, which are limited superior by l_v and inferior by 0.5 l_v. The mathematical model including the SMA actuation can be developed in two ways. First is possible to consider for position control, ONLY the length variation of the SMA actuator. This approach is a correct one, the additional torque, provided by the particular proprieties of SMA, enforces the actuation. The situation corresponds to tendon actuation or wire actuation.

Using the substitution:

$$\dot{\theta}_1 = \frac{-2l_v}{lr\sqrt{4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2}}\dot{l}_v \qquad (18)$$

$$\ddot{\theta}_1 = \frac{-2l_v}{lr\sqrt{4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2}}\ddot{l}_v - \frac{2}{lr\sqrt{4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2}}\dot{l}_v^2 - \frac{4l_v^2\left(l_v^2 - l^2 - r^2\right)}{l^3 r^3 \sqrt[3]{\left(4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2\right)^2}}\dot{l}_v^2 \qquad (19)$$

The mathematical model of the single link robot with wire actuation is:

$$\tau_1 = \left(\frac{m_1 w_1^2}{3}\right)\left(\frac{-2l_v}{lr\sqrt{4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2}}\ddot{l}_v - \frac{2}{lr\sqrt{4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2}}\dot{l}_v^2 - \frac{4l_v^2\left(l_v^2 - l^2 - r^2\right)}{l^3 r^3 \sqrt[3]{\left(4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2\right)^2}}\right) +$$

$$- \frac{4l_v^2\left(l_v^2 - l^2 - r^2\right)}{l^3 r^3 \sqrt[3]{\left(4 - \left(\frac{l_v^2 - l^2 - r^2}{lr}\right)^2\right)^2}}\Bigg) +$$

$$\frac{g m_1 w_1\left(l_v^2 - \left(r^2 + l^2\right)\right)}{4lr} + b_1\left(\theta_1\right) \qquad (20)$$

Analyzing the equilibrium conditions, results that $\tau_1 = b_1\left(\theta_1\right)$ and $l_v^2 = r^2 + l^2$, state which correspond to real case.

Second way makes a simplifying assumption: because the SMA connection with single link structure can be choose near to the articulation point, we can assume that the entire SMA torque is directly used for movement[15]. Then the mathematical model can be expressed as:

$$\tau_{SMA} = \left(\frac{m_1 w_1^2}{3}\right)\ddot{\theta}_1 + \frac{g m_1 w_1 \cos(\theta_1)}{2} + b_1(\theta_1) \qquad (21)$$

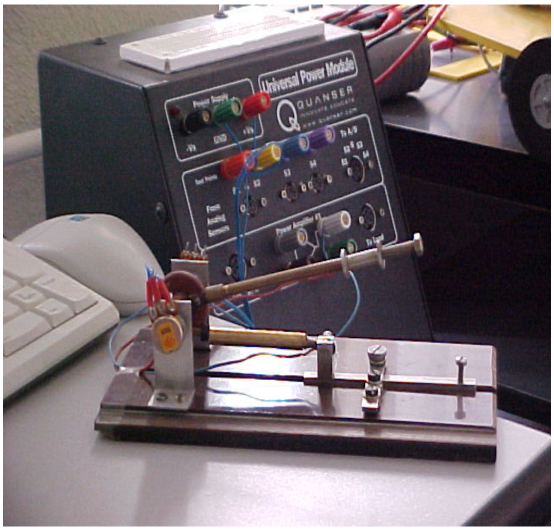

Fig. 8 Experimental model for a single link robotic structure

4 Control Applied To Shape Memory Alloy Serial Link Robotic Structure

4.1 Fuzzy Control Applied To Shape Memory Alloy Serial Link Robotic Structure

Theoretical models and numerical simulation [9], [16], [17] was successfully developed. The promising numerical simulation results are a strong support in developing experiments for 1, 2 serial robotic links, for the beginning.

In order to investigate the SMA robotic structure comportment a Quanser modified platform was used for experiments. The basic control structure uses a configurable PID controller and a Quanser Power Module Unit for energizing the SMA actuators.

PID controller was changed, in order to adapt to the particularities of the SMA actuator. A negative command for SMA actuator corresponds to a cooling source.

The actual structure do not use for cooling other devices, excepting the ambient temperature.

The PI experimented controller parameters are: the proportional parameter K_R = 10 and the integration parameter is K_I =0, 05. The input step is equivalently with 30^0 angle base variation and the evolution of this reference is represented with the response of real system in Fig. 10.

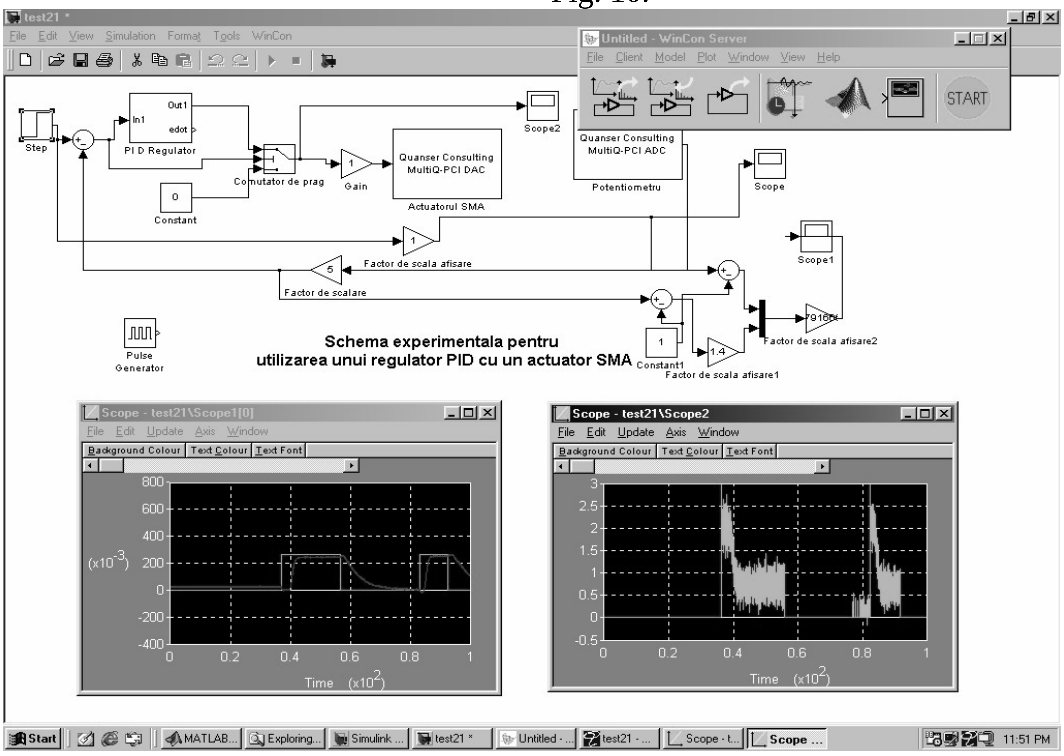

Fig.9 Shape memory alloy actuation structure

The control signal variation is presented in Fig. 11.

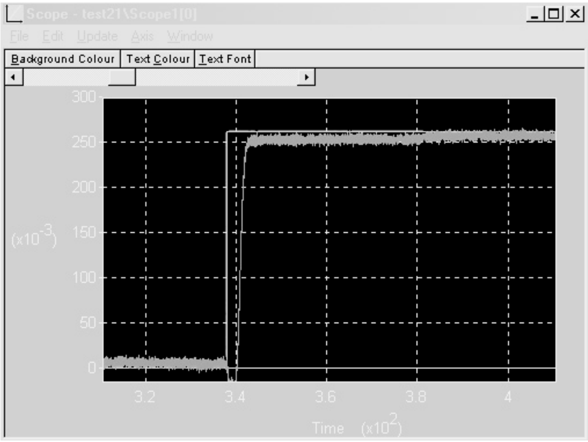

Fig. 10 System response, for step input

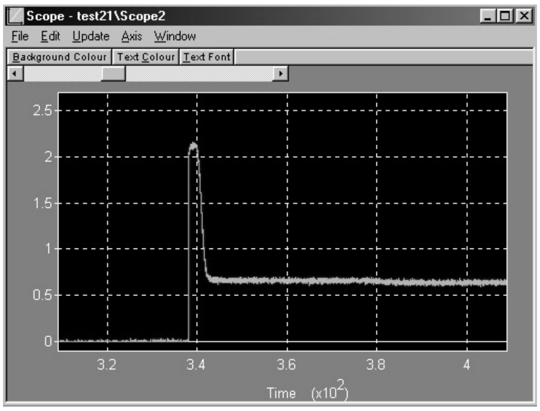

Fig. 11 PI controller response, for step input

For negative step, the evolution of the system and the control variable evolution are presented in Fig. 12 and Fig. 13.

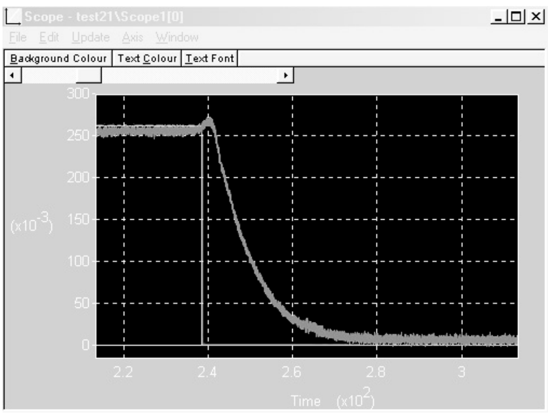

Fig. 12 System responses, negative step input

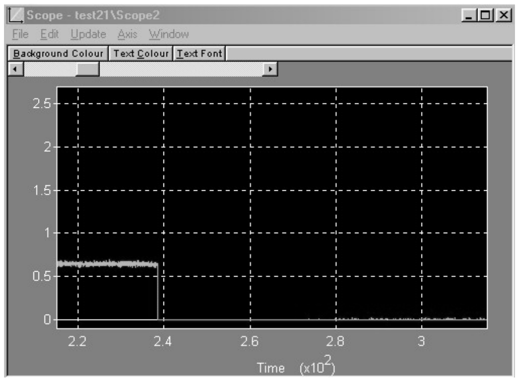

Fig. 13 PI controller response, negative step

The PD experimented controller parameters are: the proportional parameter $K_R = 10$ and the derivative parameter is $K_D = 2$.

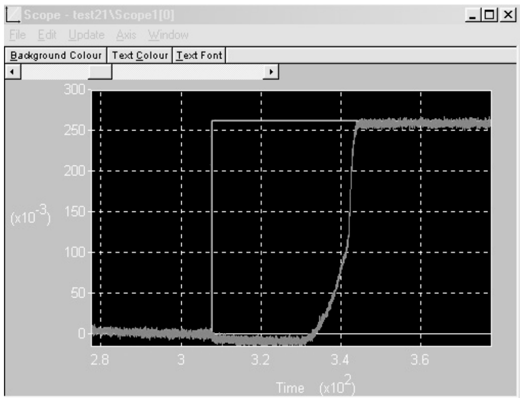

Fig. 14 System response, step input

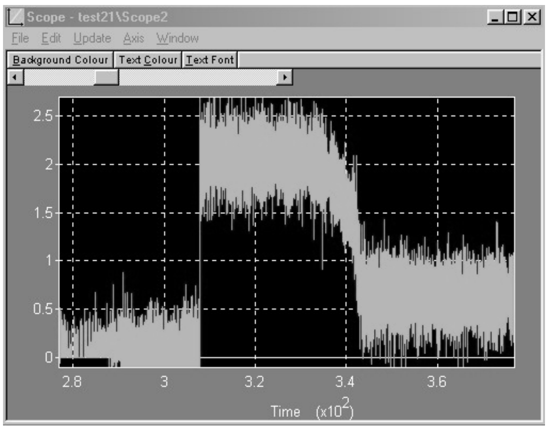

Fig. 15 PD controller response, step input

One can observe the high dynamics of the control variable – Fig. 15. The time response is longer then the case of PI controller, but the stationary error is less then the anterior case – Fig.14.

The PID experimented controller parameters are: the proportional parameter K_R=10 and the integration component is K_I=0,005 and the derivative component is K_D=2.

The experimental results are illustrated in the figure, and the control signal variation is presented in Fig. 16 and Fig. 17.

Unfortunately, even with the complication of the controller, the time response is inferior to the case of the PI controller and the stationary error is near zero.

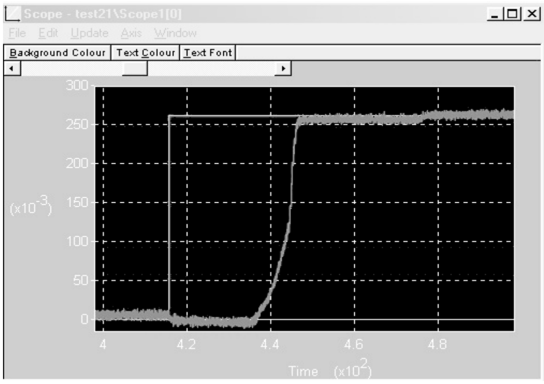

Fig 16 System response, step input

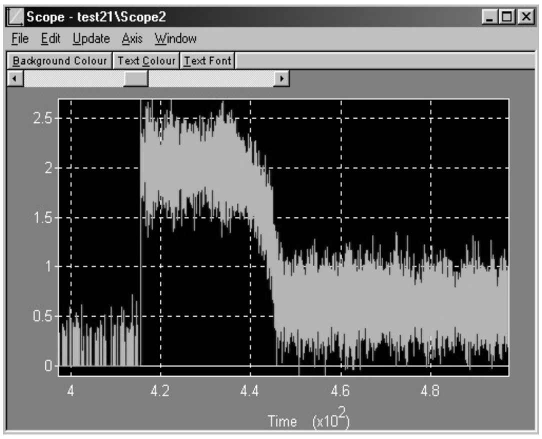

Fig. 17 PID controller response, step input

As a conclusion: the best results arise when a PI controller is used. The PI experimented controller parameters are: the proportional parameter K_R = 10 and the integration parameter is K_I =0, 05.

Using PID, PD controller the experiments conduct to less convenient results from the point of view of time response or controller dynamics.

Using heat in order to activate SMA wire, a human operator will increase or decrease the amount of heat in order to assure a desired position to robotic link.

Because of medium temperature influence, can not be establish, apriority, a clear control law, available for all the points of the robotic structure workspace. Using the fuzzy theory, a simple and efficient control structure can be implemented:

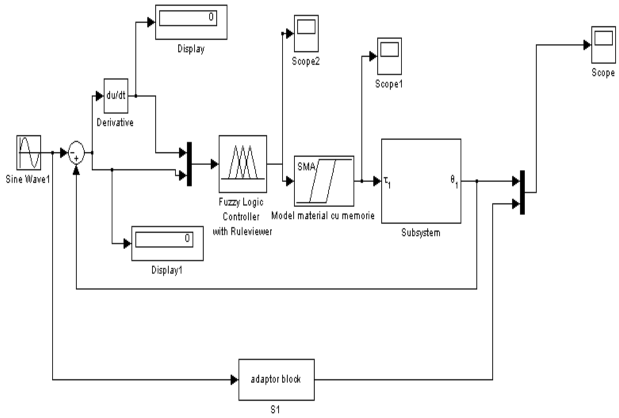

Fig. 18 Fuzzy control structure

For an efficient control we propose the following definition for the input and output members:

- input 1 is the first derivate of position error, with 3 fuzzy member: Negative, Zero, Positive;

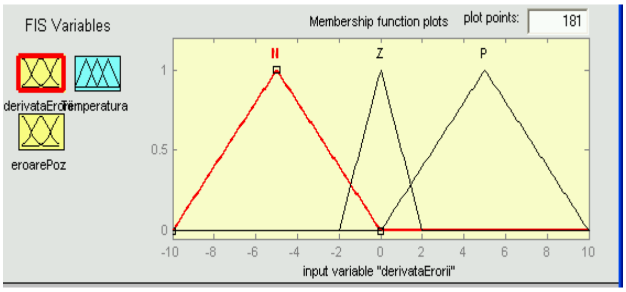

Fig. 19 Fuzzy input 1 member

- input 2 is position error with 3 fuzzy member : Negative, Zero and Positive

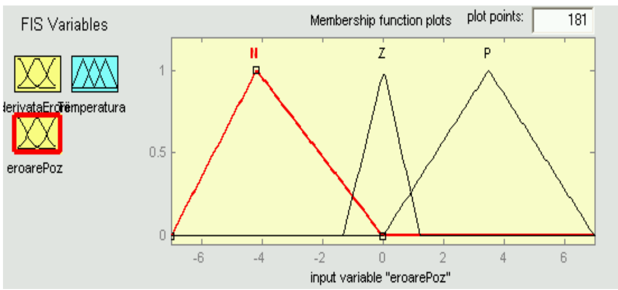

Fig. 20 Fuzzy input 2 members

Output is temperature heating with 3 fuzzy members: Temperature Negative (temperature under austenitic start transformation), Temperature Zero (temperatures between start and final austenitic transformation), Temperature Positive (temperature above temperature of final austenitic transformation).

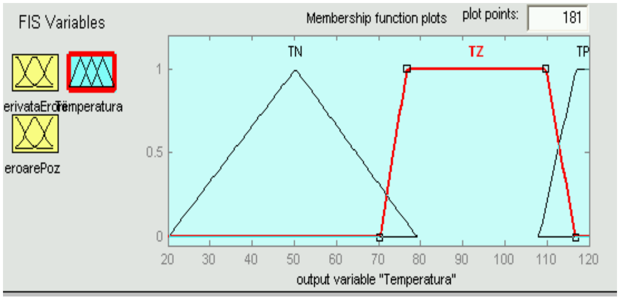

Fig. 21 Fuzzy output members

The rules are very simple and are illustrated in the next table:

Table 1. The fuzzy rules for proposed controller

e \ $\dot{e}$	P	Z	N
P	TP	TP	TP
Z	TZ	TZ	TZ
N	TN	TN	TN

The result of the numerical simulation are promising, related to the simplicity of the control structure, for the case of the sinusoidal reference with frecvency of 5 rad/sec.

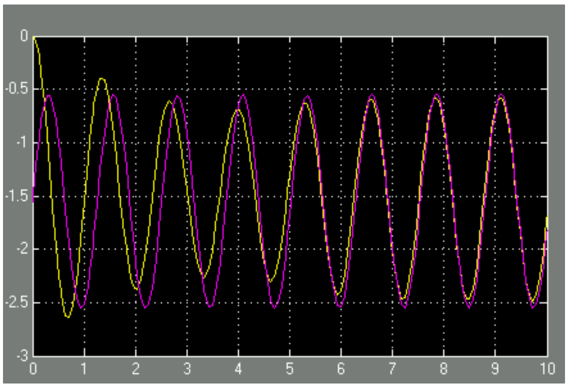

Fig. 22 Fuzzy robotic structure output evolution

5 Conclusion

The simulations and the mathematical model developed in the article offer a background in studying the serial link robotic control possibilities.

The results respect the real evolution of the structure. In the future, the authors will explore all the control possibilities applied to a real tentacle model – Fig.23, witch for the moment is under construction.

Fig. 23 Experimental model for a two module tentacle robotic structure

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