FUZZY CONTROL FOR SHAPE MEMORY ALLOY TENDON ACTUATED 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. In order to assure an efficient control of SMA actuator applied to inverted pendulum, a mathematical model and numerical simulation of the resulting model is required. Due a particular possibility SMA actuator connection, a modified dynamics for wire or tendon actuation is presented. For an efficient study a Simulink block set is developed (block for user configurable shape memory alloy material, configurable block for dynamics of single link robotic structure, block for user configurable wire/tendon actuation). As conventional control possibilities were explored, the fuzzy control structure applied in this paper, offer an improved response. A more compact SMA actuation is proposed and experimented. The results are commented.

Key-Words: - robotics, shape memory alloy applications, serial link, fuzzy controller

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.

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.

The basic rule for electrical actuation is that the temperature of complete transformation to martensite M_f, 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.

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. 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.
A fuzzy controller is composed of the three calculation steps Fuzzification, Fuzzy Inference and Defuzzification. The control strategy 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.
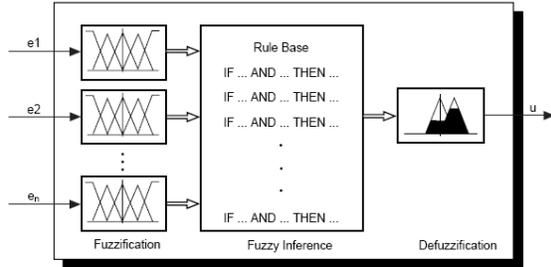
Fig.1. A fuzzy controller structure

Sliding mode control 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. 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.

2 Dynamics Of Two-Link Tendon-Driven Robotic Structure

There are many methods for generating the dynamic equations of mechanical system. 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. We consider that each link is a homogeneous rectangular bar with mass mi and moment of inertia tensor

$$I_i = \begin{bmatrix} I_{xi} & 0 & 0 \\ 0 & I_{yi} & 0 \\ 0 & 0 & I_{zi} \end{bmatrix}$$

(1.)

Letting $v_i \in R^3$ be the translational velocity of

the centre of mass for the ith link and $\omega_i \in R^3$ be angular velocity, the kinetic energy of the manipulator is:

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

$$+ \frac{1}{2} m_1 \omega_2^T I_2 \omega_2 \qquad (3.)$$

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 Lagranage methods results:

$$\begin{bmatrix} \alpha + \beta c_2 & \delta + \frac{1}{2}\beta c_2 \\ \delta + \frac{1}{2}\beta c_2 & \delta \end{bmatrix} \begin{bmatrix} \ddot\theta_1 \\ \ddot\theta_2 \end{bmatrix} + \begin{bmatrix} -\frac{1}{2}\beta s_2 \dot\theta_2 & -\frac{1}{2}\beta s_2 (\dot\theta_2 + \dot\theta_1) \\ \frac{1}{2}\beta s_2 \dot\theta_1 & 0 \end{bmatrix} \bullet$$

$$\bullet \begin{bmatrix} \dot\theta_1 \\ \dot\theta_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \qquad (4.)$$

where

$$\alpha = \frac{m_1}{12}(l_1^2 + w_1^2) + \frac{m_2}{12}(l_2^2 + w_2^2) + m_1 r_1^2 + m_2 (l_1^2 + r_2^2)$$
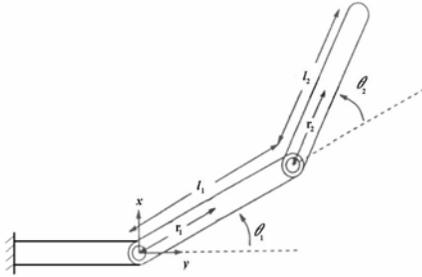
Fig.2. Two link robotic architecture

$$\beta = m_2 l_1 l_2 ; \; \delta = \frac{m_2}{12}(l_2^2 + w_2^2) + m_2 r_2^2$$

with w_1, w_2, l_1, l_2 the width and respectively the length of link 1 and link 2.

3 Shape Memory Actuator Structure

Due the actuation architecture a simple mathematical model can be establish. Schematically the shape memory actuation is:
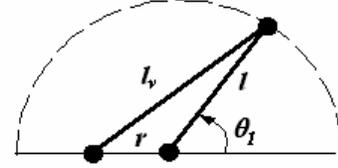
Fig.3. Shape memory alloy actuation structure

In Figure 5 the lv 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:

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

$$(5.)$$

The graphic of θ1 as function of lv is the following, considering the real domain variation for $\theta_1 \in [0, \pi]$.
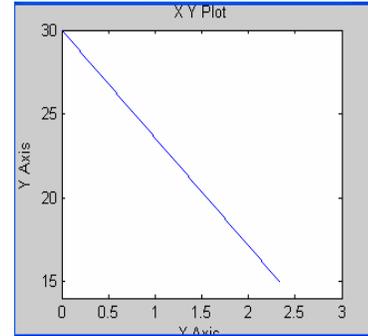
Fig.4. The graphic $l_v = f(\theta_1)$.

As can easily see the dependence is linear, that the liniarisation in modeling can be done successfully.The explanations concern the structural variation of SMA actuator, which are limited superior by lv and inferior by 0.5 lv.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:

$$\dot{\theta}_1 = \frac{-2l_v}{lr\sqrt{4-\left(\frac{l_v^2-l^2-r^2}{lr}\right)^2}} i_v \qquad (6.)$$

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

$$-\frac{4l_v^2\left(l_v^2-l^2-r^2\right)}{l^3r^3\sqrt[3]{\left(4-\left(\frac{l_v^2-l^2-r^2}{lr}\right)^2\right)^2}} \dot{i}_v^2 \quad (7.)$$

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

$$\tau_1 = \left(\frac{m_1w_1^2}{3}\right)\left(\frac{-2l_v}{lr\sqrt{4-\left(\frac{l_v^2-l^2-r^2}{lr}\right)^2}} \ddot{i}_v - \frac{2}{lr\sqrt{4-\left(\frac{l_v^2-l^2-r^2}{lr}\right)^2}} \dot{i}_v^2 -\right.$$

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

$$+\frac{gm_1w_1\left(l_v^2-\left(r^2+l^2\right)\right)}{4lr} + b_1(\theta_1) \qquad (8.)$$

Analyzing the equilibrium conditions, results that $\tau_1 = b_1(\theta_1)$ 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. Then the mathematical model can be expressed as:

$$\tau_{SMA} = \left(\frac{m_1w_1^2}{3}\right)\ddot{\theta}_1 + \frac{gm_1w_1\cos(\theta_1)}{2} + b_1(\theta_1) \qquad (10.)$$

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

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.
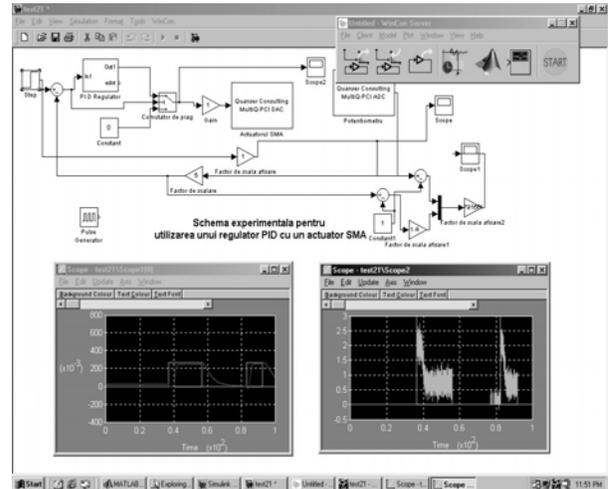
Fig.5. Quanser modified platform

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 use for cooling only the ambient temperature.

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 $K_I = 0, 05$. $\qquad (9.)$

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 Figure 5.

The control signal variation is presented in Figure 6.
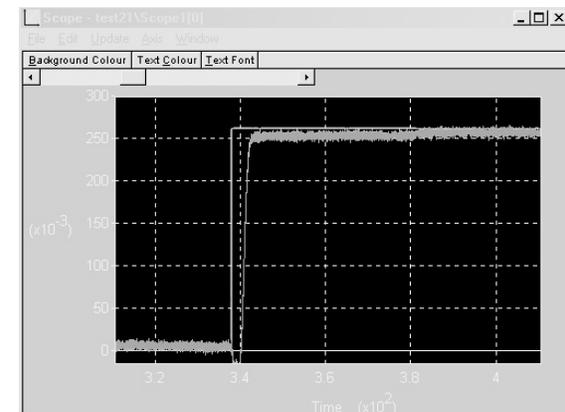
Fig.5. System response, for step input
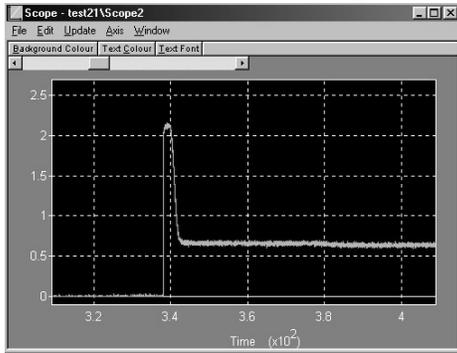
Fig.6. PI controller response, for step input

For negative step, the evolution of the system and the control variable evolution are presented in Figure 7 and Figure 8.
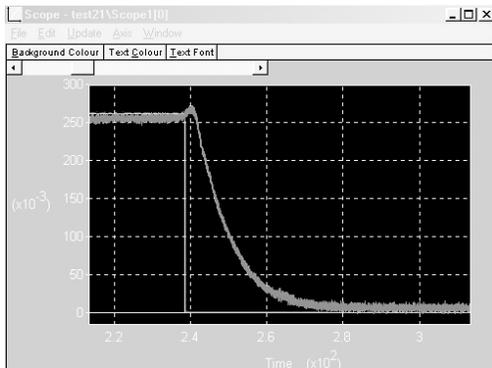
Fig.7. System response, negative step input
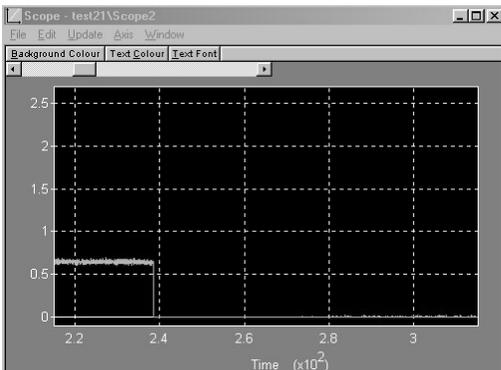
Fig.8. PI controller response, negative step

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, apriori, a clear control law, available for all the points of the robotic structure

workspace. Using the fuzzy theory, a simple and efficent control structure can be implemented:
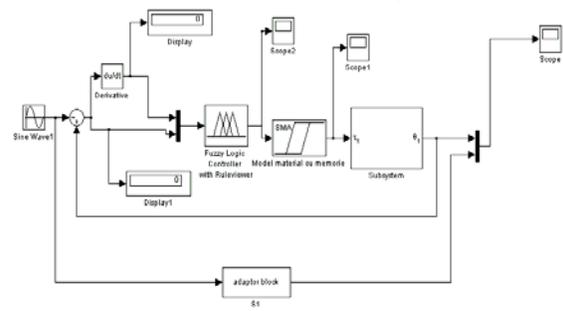
Fig.9. Fuzzy control structure

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

−   input 1 is the first derivate of pozition error, with 3 fuzzy member: Negative, Zero, Pozitive;
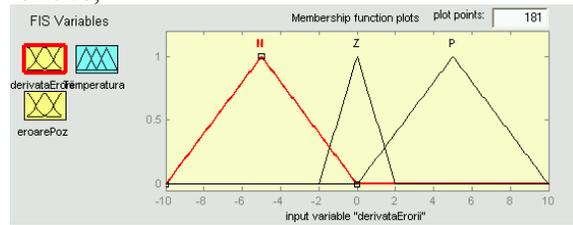
Fig.10. Fuzzy input 1 members

−   input 2 is pozition error with 3 fuzzy member : Negative, Zero and Pozitive
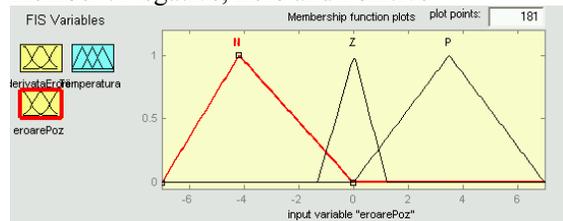
Fig.11. Fuzzy input 2 members

Output is temperature heating with 3 fuzzy member: 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)
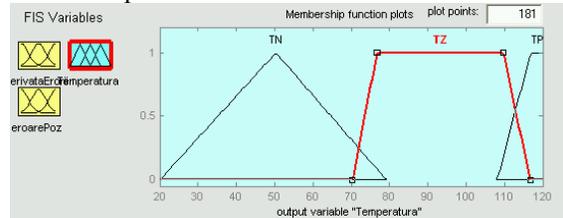
Fig.12. Fuzzy output members

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

Table 1 The fuzzy rules for proposed controller

$\dot{e}$	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.
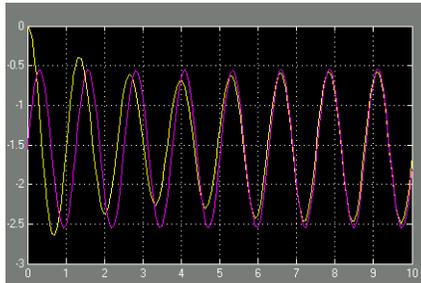
Fig.13. Fuzzy robotic structure output evolution

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 model; witch for the moment is under construction.
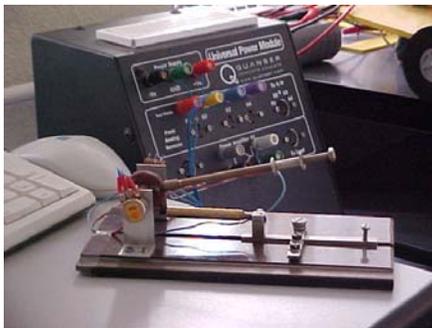
Fig.14. Experimental model for a single link robotic structure

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