SHAPE MEMORY ALLOY TENDONS ACTUATED TENTACLE ROBOTIC STRUCTURE

Models and Control

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Abstract: A tentacle manipulator is a manipulator with a great flexibility, with a distributed mass and torque that can take any arbitrary shape. Technologically, such systems can be obtained by using a cellular structure for each element of the arm. Shape memory alloy actuation offers 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.

1 INTRODUCTION

Shape Memory Alloy (SMA) are materials that, once mechanically deformed at given temperature, are able to recover the deformation through an appropriate thermal cycle (Funakubo, 1987).

Between the alloys that show this property, attention has been focused on Nickel – Titanium alloy: it show properties which are suitable for the applications in robotics, general propose actuator and medicine (Faravelli and Marioni, 1996). The nickel titanium alloys, generally refereed to as Nitinol 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. Other important proprieties of the Nitinol, superelasticity (or pseudoelasticity) refers to the ability of NiTi to return to its original shape upon unloading after a substantial deformation.

This is based on stress-induced martensite formation. The application of an outer stress causes martensite to form at temperatures higher than M_s.

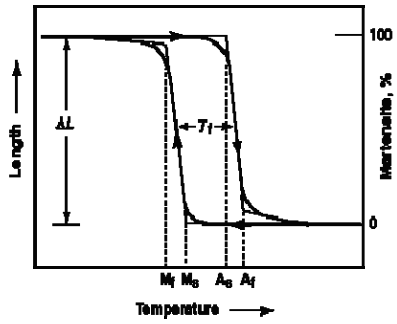

Figure 1: Martensitic and Austentic transformations.

The macroscopic deformation is accommodated by the formation of martensite. When the stress is released, the martensite transforms back into austenite and the specimen returns back to its original shape. Superelastic NiTi can be strained several times more than ordinary metal alloys

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without being plastically deformed, which reflects its rubber-like behavior. It is, however, only observed over a specific temperature area. The highest temperature at which martensite can no longer stress induced is called Md. Above M_d NiTi alloy is deformed like ordinary materials by slipping. Below as temperature, the material is martensitic and does not recover. Thus, superelasticity appears in a temperature range from near A_f and up to M_d. The largest ability to recover occurs close to A_f.

Another important feature of superelastic materials is that their unloading curves are flat over large strains. Thus, the force applied by a superelastic device is determined by the temperature, not by the strain as in conventional Hookian materials. 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.

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..

Using the kinetic energy and Lagrange methods results:

$$\begin{bmatrix} \alpha+\beta c_2 & \delta+\frac{1}{2}\beta c_2 \\ \delta+\frac{1}{2}\beta c_2 & \delta \end{bmatrix}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}+\begin{bmatrix} -\frac{1}{2}\beta s_2\dot{\theta}_2 & -\frac{1}{2}\beta s_2\left(\dot{\theta}_2+\dot{\theta}_1\right) \\ \frac{1}{2}\beta s_2\dot{\theta}_1 & 0 \end{bmatrix}\bullet$$

$$\bullet\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}=\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{1}$$

Where

$$\alpha=\frac{m_1}{12}\left(l_1^2+w_1^2\right)+\frac{m_2}{12}\left(l_2^2+w_2^2\right)+m_1r_1^2+m_2\left(l_1^2+r_2^2\right) \tag{2}$$

$$\beta=m_2l_1l_2 \tag{3}$$

$$\delta=\frac{m_2}{12}\left(l_2^2+w_2^2\right)+m_2r_2^2 \tag{4}$$

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

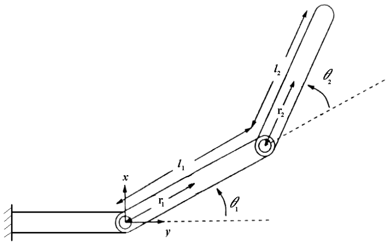

Figure 2: Two link robotic architecture.

3 SHAPE MEMORY ACTUATOR STRUCTURE

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

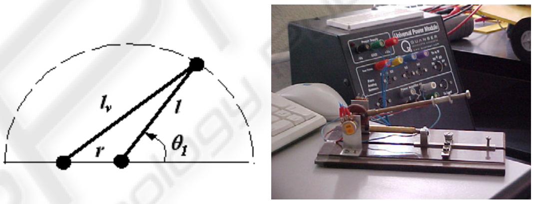

Figure 3: Shape memory alloy actuation structure.

In Figure 3 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

$$\theta_1=\arccos\left(\frac{l_v^2-\left(r^2+l^2\right)}{2lr}\right)\Leftrightarrow\theta_1=f\left(l_v^2\right) \tag{5}$$

The graphic of θ_1 as function of lv (considering the real domain variation for $\theta_1\in\left[0,\pi\right]$) 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 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:

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

$$\ddot{\theta}_1 = \frac{-2l_v}{lr\sqrt{4-\left(\frac{l_v^2-l^2-r^2}{lr}\right)^2}}\ddot{l}_v - \frac{2}{lr\sqrt{4-\left(\frac{l_v^2-l^2-r^2}{lr}\right)^2}}\dot{l}_v^2 - \frac{4l_v^2\left(l_v^2-l^2-r^2\right)}{l^3r^3\sqrt[3]{\left(4-\left(\frac{l_v^2-l^2-r^2}{lr}\right)^2\right)^2}}\dot{l}_v^2 \tag{7}$$

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. Then the mathematical model can be expressed as

$$\tau_{SMA} = \left(\frac{m_1w_1^2}{3}\right)\ddot{\theta}_1 + \frac{gm_1w_1\cos\left(\theta_1\right)}{2} + b_1\left(\theta_1\right) \tag{8}$$

4 CONTROL OF SHAPE MEMORY ALLOY TENTACLE 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.

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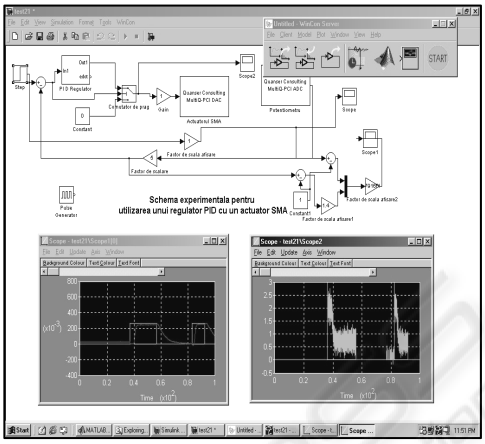
PID controller was changed, in order to adapt to the particularities of the SMA actuator. A negative command for SMA actuator corresponds to a cooling source. The actual structure use for cooling only the ambient temperature.

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.



Schema experimentala pentru utilizarea unui regulator PID cu un actuator SMA

Figure 4: Quanser modified platform.

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.

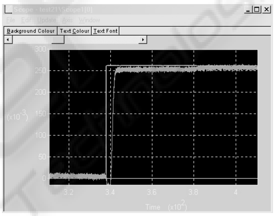


Figure 5: System response, for step input.

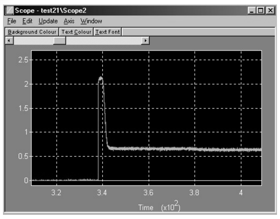


Figure 6: PI controller response, for step input.

For negative step, the evolution of the system and the control variable evolution are presented in Figure 7 and Figure 8.

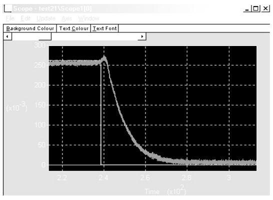


Figure 7: System response, negative step input.

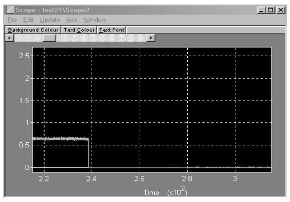


Figure 8: PI controller response, negative step input.

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. A simple and efficent control structure can be implemented.

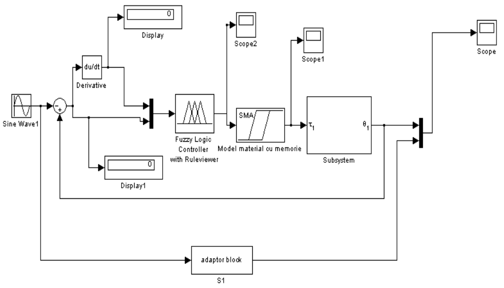


Figure 9: Fuzzy control structure.

For an efficient control it is proposed the following definition for input and output members:
- input 1 is the first derivate of pozition error, with 3 fuzzy member: Negative, Zero, Pozitive
- input 2 is pozition error with 3 fuzzy member: Negative, Zero and Pozitive
- 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).

Table 1: Fuzzy rules for the proposed controller.

$\dot{e}$ 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.

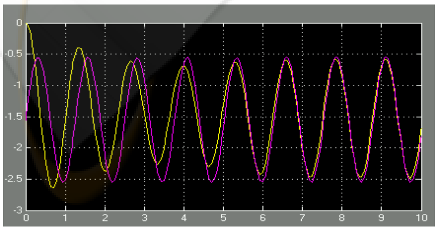


Figure 10: Fuzzy robotic structure output evolution.

5 CONCLUSIONS

The simulations, the mathematical model and the initial experiments 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 improvement of the control performnces and the extension of the experiments to n link robotic structure.

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