Fuzzy Logic Controller for Shape Memory Alloy Tendons Actuated Biomimetic Robotic Structure

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Abstract: The paper studies the fuzzy logic controller for a shape memory alloy (SMA) biomimetic (tentacle type) robotic structure. A tentacle manipulator is a manipulator with a great flexibility, with a distributed mass and torque that can take any arbitrary shape. Considering the influences of the environment temperature, for SMA actuation, a special attention has to be paid to the adaptation of control strategy to external condition. First, are presented experimental results related to SMA physical characterizations using Thermal Analysis Methods. In the next section SMA tentacle’s robotic structure conventional control (P, PI, PD, and PID controller) is tested and the results are commented. Fuzzy logic approach conducts to suitable for the tentacle SMA based structure, considering the repeatability of the results. The proposed control strategy is based on the Direct Sliding Mode Control (DSMC), which controls the trajectory, towards the switching line and then the motion is forced directly to the origin, on the switching line. A fuzzy controller is proposed and the fuzzy rules are established by using the DSMC procedures. In conclusions conventional control structures offer good performances in term of the time response and simple structure, but not guarantee the repeatability of the results as proposed DSMC controller.

Key words: Direct Sliding Mode Controller, Fuzzy Logic Sliding Mode Control, Robot, Shape Memory Alloy.

INTRODUCTION

In the past few years, the research in coordinating robotic systems with multiple chains has received considerable attention. The problem of controlling this system in real time is more complicated. A multiple chain tentacle robotic system is very complicated. The control can be produced using an electrohydraulic or pneumatic action that determines the contraction or dilatation of the peripheral cells, or can be used shape memory alloy tendons for tentacle actuation. A suitable model for SMA tendons actuated biomimetic robot (tentacle type) is presented in [BIZ 06]. 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. Defining a fuzzy controller, process control can be easily implemented. 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. 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. 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.

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 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.
Unfortunately forcing the outputs of controller to conduct the system error after a straight trajectory to zero produce strong outputs dynamics and big value of outputs requirements.

In order to offer better performances and to compensate the difficult to implement output requirements, recent research in this field combine fuzzy logic control strategies with adaptive control [HWA 06], neural networks [KHO 07], sliding mode control strategies [ZHU 06] [ZHO 07].

1. Fundamental characteristics of shape memory alloys

The unique behavior of SMA’s is based on the temperature-dependent austenite-to-martensite phase transformation on an atomic scale, which is also called thermoelastic martensitic transformation. The thermoelastic martensitic transformation causing the shape recovery is a result of the need of the crystal lattice structure to accommodate to the minimum energy state for a given temperature [OTS 98].

The shape memory metal alloys can exist in two different temperature-dependent crystal structures (phases) called martensite (lower temperature) and austenite (higher temperature or parent phase).

When martensite is heated, it begins to change into austenite and the temperatures at which this phenomenon starts and finishes are called austenite start temperature ($A_s$) and respectively austenite finish temperature ($A_f$). When austenite is cooled, it begins to change into martensite and the temperature at which this phenomenon starts and finishes are called martensite start temperature ($M_s$) and respectively martensite finish temperature ($M_f$) [BUE 67]. Several properties of austenite and martensite shape memory alloys are notably different. Martensite is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures. The molecular structure in this phase is twinned. Austenite is the stronger phase of shape memory alloys, which exists at higher temperatures. In Austenite phase the structure is ordered, in general cubic.

The thermoelastic martensitic transformation causes the following properties of SMA’s [WAR 93] [VAN 99] [VAN 01].

One-way shape memory effect represents the ability of SMA to automatically recover the high temperature austenitic shape upon heating, but it is necessary to apply a force to deform the material in the low temperature martensitic state.

Two-way shape memory effect or reversible shape memory effect represents the ability of SMA’s to recover a preset shape upon heating above the transformation temperatures and to return to a certain alternate shape upon cooling. Note that both the one-way and two-way shape memory effects can generate work only during heating (i.e. force and motion) [NAS 05].

All-round shape memory effect is a special case of the two-way shape memory effect [SHI 87]. This effect differs from the two-way effect in the following ways:

- a greater amount of shape change is possible with the all-around effect,
- the high and low temperature shapes are exact inverses of each other, that is a complete reversal of curvature is possible in the case of a piece of shape memory strip.

Hysteresis behavior. Due to processes which occur on an atomic scale, a temperature hysteresis occurs. In other words the austenite to martensite transformation (the “forward reaction”) occurs over a lower temperature range than the martensite to austenite transformation.

The difference between the transition temperatures upon heating and cooling is called hysteresis. Most SMA’s have a hysteresis loop width of 10-50°C.

Superelasticity can be defined as the ability of certain alloys to return to their original shape upon unloading after a substantial deformation has been applied.

Vibration damping capacity. Due to the special micro structural behavior, SMA’s exhibit the highest vibration damping property of all metal materials.

The damping is non-linear and frequency independent, but it’s sensitive to temperature variations and the antecedents of thermal cycling.

2. Design strategies for SMA elements

The first step an engineer should take when undertaking a design involving shape memory material is to clearly define the design requirements.

These usually fall into one of the following interrelated areas: operating mode, mechanical considerations, transformation temperatures, force and/or motion requirements, and cyclic requirements.

2.1. Operating modes of SMA’s

The most used operating modes of SMA’s are:

- **Free recovery** which consists of three steps: shape memory material deformation in the martensitic condition at low temperature, deforming stress release, and heating above the $A_s$ temperature to recover the high temperature shape. There are few practical applications of the free recovery event other than in toys and demonstrations.

- **Constrained recovery** is the operation mode used for couplings, fasteners, and electrical connectors.

- **Work production** – actuators. In this operation mode a shape memory element, such as a helical springs or a strip, works against a constant or varying force to perform work [HOF 06].
The element therefore generates force and motion upon heating.

2.2. Mechanical considerations and design assumptions

The most successful applications of shape memory alloy components usually have all or most of the following characteristics [DEG 03]:

- A mechanically simple design.
- The shape memory component "pops" in place and is held by other parts in the assembly.
- The shape memory component is in direct contact with a heating/cooling medium.
- A minimum force and motion requirement for the shape memory component.

The shape memory component is isolated ("decoupled") from incidental forces with high variation. The tolerances of all the components realistically interface with the shape memory component [BIZ 04].

2.3. Transformation temperatures

The force that a spring or a strip of any material produces at a given deflection depends linearly on the shear modulus (rigidity) of the material. SMA's exhibit a large temperature dependence on the material shear modulus, which increases from low to high temperature. Therefore, as the temperature is increased the force exerted by a shape memory element increases dramatically [DOL 01]. Consequently the determination of the transformation temperatures is necessary to establish the shear modulus values at these functional temperatures for a high-quality design. This section presents the transformation temperatures obtained for the studied SMA elements (strip and helical spring) using Thermal Analysis Methods. Ni-Ti-Cu (Raychem proprietary alloy) is the material used for the two SMA elements. Thermal Analysis Methods comprises a group of techniques in which a physical property of a sample is measured as a function of temperature, while the sample is subjected to a controlled temperature program.

Thermogravimetric Analysis (TGA), Differential Thermal Analysis (DTA) and Differential Scanning Calorimetry (DSC) methods were used to determine the required parameters.

TGA is a technique which relies on samples that decompose at elevated temperatures. The TGA monitors changes in the mass of sample on heating.

In DTA, the temperature difference that develops between a sample and an inert reference material is measured, when both are subjected to identical heat-treatments. DTA can be used to study thermal properties and phase changes.

The related technique of DSC relies on differences in energy required to maintain the sample and reference at an identical temperature.

The DTA and DSC curves use a system with two thermocouples. One of them is placed on the sample and the other on the reference material. In this paper, both isothermal and non-isothermal regimes combined with heating-cooling experiments, were used in order to characterize SMA test samples. The measurements were carried out on a Perkin Elmer Thermobalance in dynamic air atmosphere, in the aluminium crucible. The test sample's phase transitions were identified by analyzing their behavior at programmed heating up to 200°C and cooling at ambient temperature. In addition we can notice that the sample’s mass does not undergo any changes at heating and cooling. In consequence, the TGA curves are ignored in further measurements.

2.3.1. SMA strip transformation temperature

The temperature-control program used for SMA strip measurements contains the following sequences:

- heating from 30°C to 160°C at 5°C/min;
- holding for 10 min at 160°C;
- cooling from 160°C to 20°C at 5°C/min.

The measurements were carried out in dynamic air atmosphere. The results are presented in Figure 1.

![Figure 1. DTA and DSC curves for 18.275mg SMA strip](image)

By analyzing Figure 1 we can observe two phase transitions. The first occurs during the heating process while the second one appears during the cooling process. The details of these thermal effects are presented in Figure 2 and 3 (reported from the DSC curve).

Figure 2 shows that the determined transformation temperatures at heating (martensite to austenite) are $A_p=80°C$ and $A_s=111°C$. The enthalpy of the endothermal transition process is $\Delta H = 36.8858$ J/g. The temperature corresponding to maximum transformation speed is 98.79°C. The transformation temperatures at cooling (austenite to martensite) result from Figure 3: $M_s=69°C$ and $M_f=48.25°C$. The enthalpy of the exothermal transition process is $\Delta H=-28.7792$ J/g and the temperature corresponding to maximum transformation speed is 59.75°C.
2.3.2. SMA helical spring transformation temperature

The transformation temperatures of SMA helical spring are obtained by similar measurements as in the case of SMA strip, using the following temperature-control sequences:

- heating from 30°C to 100°C at 5°C/min;
- holding for 10 min at 100°C;
- cooling from 100°C to 20°C at 5 °C/min.

The form of DTA and DSC curves is similar to the ones represented in Figure 1, for 6.849 mg SMA spring sample. The determined transformation temperatures at heating (martensite to austenite) are \( A_s = 58.89°C \) and respectively \( A_f = 67.93°C \). The enthalpy of the endothermal transition process is \( \Delta H_h = 9.2 \text{ J/g} \) and the temperature corresponding to maximum transformation speed is 60.42°C.

The transformation temperatures at cooling (austenite to martensite) are \( M_s = 45°C \) and \( M_f = 33°C \), the enthalpy of the exothermal transition process is \( \Delta H_c = -5.03 \text{ J/g} \) and the temperature corresponding to maximum transformation speed is 39.07°C.

For a prescribed trajectory \( r_d \) of SMA tentacle robot, we define the object (load) motion error as:

\[
e_1 = r_d - r ; \ e_2 = \dot{r}_d - v
\]

and the object error dynamic can be rewritten:

\[
\dot{e}_L = A_2 e_L + b_2 (r_d, \dot{r}_d) + c_2 \tau
\]

where \( e_1, e_2 \) are vectors and \( \tau \) is the resultant force which assures the object motion on the trajectory. Using the dynamic of the manipulator, we obtain

\[
M \ddot{q} + C \dot{q} + D + \tau = T
\]

where \( T \) is the generalised torque, \( M, C \) are (nnx) constant matrices, \( D \) is a nonlinear vector, and \( q_i = q(s_i), T_i = T(s_i), \tau_i = \tau(s_i) \)

\[
q = \text{col}(q_1, q_2 \ldots q_n)
\]

\[
T = \text{col}(T_1, T_2 \ldots T_n)
\]

\[
\tau = \text{col}(\tau_1, \tau_2 \ldots \tau_n)
\]

We define the system error as

\[
e = q_d - q
\]

where \( q_d \) represents the desired trajectory of the tentacle manipulator. We assume the case in which is difficult to know exactly the influence of the load and we estimate as \( \tau^* \) the value of the force which assures the desired motion on the trajectory.
\[ u_F = -k_F \, \text{sgn} \, s_i \tag{8.} \]
\[ k_F \geq |\tau^* - \tau| \tag{9.} \]

where \( H(e, qd) \) represents the nonlinear part of the dynamic model and \( \tau^* \) is the estimated values of the forces required at the terminal points of the manipulator.

4. Conventional control performances

In order to investigate performances of conventional control on SMA robotic tentacle 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.

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

The best results arise when a PI controller is used.

![Figure 5. System response, for step input](image)

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 \( 30^\circ \) angle base variation and the evolution of this reference is represented with the response of real system in Figures 4. The control signal variation is presented in Figures 5.

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.

5. Design of the fuzzy logic controller

The Theorem 1 determines the conditions which assure the motion control in the neighbourhood of the switching line. In order to accelerate the motion on the switching line we can use the DSMC (Direct Sliding Mode Control) method. This motion differs by the conventional Sliding Mode [BIZ 01] by the evolution on the switching line. When the trajectory of the system penetrates the switching line, the damping coefficient is increased and the motion is forced on the switching line toward the origin without the high frequency oscillations. In Figure 7 and Figure 8 the phase plane for the conventional Sliding Mode Control and the Direct Sliding Mode Control, respectively, are presented. The DSMC motion is assured by the following Proposition:

**Proposition 1:** The DSMC control is assured if the coefficients \( k_i \) verify the condition

\[
(c_i + k_i)^2 \geq 4m\left(c_i + \sigma - m\sigma + c_i + k_i + h\right) \tag{10.}
\]

The control problem asks for determining the torques \( T \) such that the trajectory of the overall system (object and manipulator) will correspond as closely as possible to the desired behavior.

The controller receives the error and the change of the error components: \( e, \dot{e} \) for each unit of the tentacle manipulator and depending on the values of forces \( \tau_i \), generates the fuzzy control torques \( T_i \).

![Figure 7. Conventional Sliding Mode Control](image)
Figure 8. Direct Sliding Mode Control

The control problem asks for determining the manipulatable torques \( T \) such that the trajectory of the overall system (object and manipulator) will correspond as closely as possible to the desired behavior.

The control system contains two parts: the first component is a conventional controller which implements a classic strategy of the motion control based on the Lyapunov stability and the second is a Fuzzy Controller [BYU 98], [ERB 96], [SOO 97]. The controller receives the error and the change of the error components, \( e_i, \dot{e}_i \) for each units of the tentacle manipulator and depending on the values of forces \( \tau_F \), generates the fuzzy control torques \( T_F \). The control rules are determined by the motion in the neighborhood of the switching line as a variable structure controller. We adopted here a special class of SMC named DSMC (Direct Sliding Mode Control).

The physical meaning of the rules is as follows: the output is zero near the switching line, the output is negative above the switching line, the output is positive below the diagonal line, the magnitude of the output tends to increase in accordance with magnitude of the distance between the switching line and the state. The procedure for the design of the Fuzzy Controller is the following:

We consider that all input/output fuzzy sets are assured to be designed on the normalized space. The universes of the input variables \( e, \dot{e} \) are initially partition on three fuzzy sets: negative (N), zero (Z) and positive (P) with trapezoid membership function.

We consider that all input/output fuzzy sets are assured to be designed on the normalized space. The basic membership of the input variables \( e, \dot{e} \) are proposed as in Figure 9. The universes of the input variable \( e_i, \dot{e}_i \) are initially partition on three fuzzy sets: negative (N), zero (Z) and positive (P) with trapezoid membership function.

The state space of \( e, \dot{e} \) will be partitioned into nine fuzzy regions. The fuzzy if-then rules for these fuzzy regions are presented in Table 1:

![Initial input fuzzy sets- 3 members](image)

**Table 1.** The initial fuzzy if-then rules

where the output membership are defined as singletons. The output \( u_F \) of the fuzzy controller is derived to be

\[
 u_F = \frac{\sum_{i} \rho_i f_i(e_i)f_i(\dot{e}_i)}{\sum_{i} f_i(e_i)f_i(\dot{e}_i)} \tag{11}
\]

where \( \rho_i \) is one of the centres of the output singletons and \( f_i(e_i), f_i(\dot{e}_i) \) are the membership of the input variable \( e, \dot{e} \) respectively.

![Control trajectory](image)
The size of \( k_i \) is defined as singleton function.

If the evolution described in Figure 10 is not satisfactory, a new control strategy is adopted. The finer fuzzy domains are introduced and new fuzzy partitions are used: big negative (BN), small negative (SN), negative zero (NZ), zero (Z), and positive zero (PZ), small positive (SP), big positive (BP).

The new membership of the inputs \( \mu^* \) verify the inequality

\[
\mu^*(x_i) \leq \mu(x_i)
\]

for every input \( x_i \).

Then, new control \( u_F \) from (12) will satisfy the condition \( d \). **Theorem 1**. Also the new finer distribution of the control allows a new trajectory determined by the new values of the \( k_i \), small (S), medium (M), big (B).

**Figure 12. Output singleton – 3 members**

**Figure 13. Input fuzzy sets – 7 members**

The fuzzy if-then rules for these fuzzy regions are presented in the Table 2, where the outputs are the singletons.

**Table 2. The fuzzy if-then rules**

<table>
<thead>
<tr>
<th>( e - e_L )</th>
<th>BN</th>
<th>SN</th>
<th>NZ</th>
<th>Z</th>
<th>PZ</th>
<th>SP</th>
<th>BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>Z</td>
<td>NZ</td>
<td>SN</td>
<td>SN</td>
<td>BN</td>
<td>BN</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>PZ</td>
<td>Z</td>
<td>SN</td>
<td>SN</td>
<td>SN</td>
<td>BN</td>
<td></td>
</tr>
<tr>
<td>PZ</td>
<td>SP</td>
<td>Z</td>
<td>NZ</td>
<td>SN</td>
<td>SN</td>
<td>BN</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>SP</td>
<td>PZ</td>
<td>Z</td>
<td>SN</td>
<td>SN</td>
<td>SN</td>
<td></td>
</tr>
<tr>
<td>NZ</td>
<td>BP</td>
<td>SP</td>
<td>SP</td>
<td>PZ</td>
<td>Z</td>
<td>NZ</td>
<td>SN</td>
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<tr>
<td>SN</td>
<td>BP</td>
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<td>SP</td>
<td>SP</td>
<td>PZ</td>
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<td>NZ</td>
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<tr>
<td>BN</td>
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<td>BP</td>
<td>SP</td>
<td>PZ</td>
<td>Z</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 14. Output singleton – 7 members**

**Figure 15. The rules surface**

The result of this strategy is evaluated with the performance indexes. The procedure of the modification of the fuzzy rule base will be repeated several times until the performance requirements are satisfied.

**Figure 16. Input fuzzy sets – 13 members**

**Figure 17. Output singleton – 13 members**
6. Numerical results

The purpose of this section is to demonstrate the effectiveness of the method. This is illustrated by solving a fuzzy control problem for a tentacle manipulator system, which operates in XOZ plane. An approximate model with $\Delta=0.36$ m and $n=6$ is used. Also, the length and the mass of the object are 0.2 m and 1 kg, respectively.

![Trajectory](image)

**Figure 18. Numerical simulation for tentacle biomimetic robotic structure**

The initial positions of the arms expressed in the inertial coordinate frame are:

<table>
<thead>
<tr>
<th>TM</th>
<th>$q_1(0)$</th>
<th>$q_2(0)$</th>
<th>$q_3(0)$</th>
<th>$q_4(0)$</th>
<th>$q_5(0)$</th>
<th>$q_6(0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>$\pi/6$</td>
<td>$\pi/3$</td>
<td>$7\pi/12$</td>
<td>$2\pi/3$</td>
<td>$\pi/15$</td>
<td>$15\pi/8$</td>
</tr>
</tbody>
</table>

**Table 3. Initial positions of the arms**

The desired trajectory of the terminal points is defined by: $x=x_0+at$; $z=z_0+bt$ with $a=0$, 10; $b=0$, 25; $x_0=0.25$ m; $z_0=0.375$ m.

The trajectory lies the work envelope and does not go through any workspace singularities. The maximum force constraints are defined by:

$$F_x \leq F_{\text{max}} = 50N$$

$$F_z \leq F_{\text{max}} = 50N ;$$

and the optimal index: $\min \left( \sum_j F_x^2 \right), \min \left( \sum_j F_z^2 \right)$

are used. The uncertainty domain of the mass is defined as $0.8kg \leq m \leq 1.4kg$.

The solution of the desired trajectory for the elements of the arm is given by solving the nonlinear differential equation

$$\dot{q}_a(t) = J^T(q) \left[ J(q) \right]^{-1} J^T(q) \dot{w}(t) \quad (13)$$

where $w=(x,z)^T$ and $J(q)$ is the Jacobean matrix of the arm.

![Error Plot](image)

**Figure 19. Trajectory in the plane $(e_x, e_z)$ for fuzzy SMC procedure**

![Error Plot](image)

**Figure 20. Trajectory in the plane $(e_x, e_z)$ for fuzzy DSMC procedure**

Figure 19 represents the trajectory in the plane $(e_x, e_z)$ for fuzzy SMC procedure and Figure 20 the same trajectory for a DSMC procedure for a new switching line. We can remark the error during the 1th cycle and the convergence to the desired trajectory during the 2nd cycle.

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7. Conclusions

In this paper a Direct Sliding Mode Fuzzy Controller for SMA tentacle robotic structure is applied and some numerical simulations are provided. The controller is tested using a model of the tentacle structure. Further research will be focused on experimental tests using fuzzy control to our experimental SMA tentacle structure. The fuzzy controller offer better performances in term of the repeatability of the results (precision, time response) without ambient temperature control.
REFERENCES


