SMA CONTROL FOR BIO-MIMETIC FISH LOCOMOTION

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Abstract: In this paper, we describe our current work on bio-inspired locomotion systems using smart materials. The aim of this work is to investigate alternative actuation mechanisms based on smart materials, exploring the possibility of building motor-less and gear-less robots. A swimming underwater robot is being developed whose movements are generated using such materials, concretely Shape Memory Alloys. This paper focuses on the actuators control in order to obtain a a sufficiently fast and accurate positioning.

1 INTRODUCTION

Robotics actuator technology is basically dominated by two kind of actuators: electric motors/servomotors and pneumatic/hydraulic actuators. In mobile robotics, the former is mostly used, with exceptions being e.g. large legged robots. The (rotatory) motion of the motors is then transmitted to the effectors through gearboxes, belts and other mechanical devices in the case that linear actuation is needed. Although applied with success in uncountable robotic devices, such systems can be complex, heavy and bulky[1]. In underwater robots, propellers are most used for locomotion an maneuvering. Propellers however may have problems of cavitation, noise, efficiency, can get tangled with vegetation and other objects and can be dangerous for sea life.

Underwater creatures are capable of high performance movements in water. Thus, underwater robot design based on the mechanism of fish locomotion appears to be a promising approach. Over the past few years, researches have been developing underwater robots based on underwater creatures swimming mechanism (Hu, 2006), (Anderson and Chhabra, 2002), (Morgansen et al., 2007). Yet, most of them still rely on servomotor technology and a structure made of a discrete number of elements. One of the most advanced fishe-like robot is the MIT fish (Valdivia y Alvarado and Youcef-Toumi, 2006). This fish has a continuous soft body. A single motor generates a wave that is propagated backwards in order to generate propulsion.

In the last years, actuation technology in active or ”smart” materials has opened new horizons as far as simplicity, weight and dimensions. New materials such as piezo-electric fiber composite, electro-active polymers and shape memory alloys (SMA) are being investigated as a promising alternative to standard servomotor technology. The potential gain in weight and dimension would allow building lighter and smaller robots, and even devising soft-bodied robots (Cowan and Walker, 2008).

In order to reproduce the undulatory body motion of fishes, smart materials appear to be extremely suited. In fact, over the last years, there has been an increasing activity in this field. Research in the field of smart materials for underwater locomotion is focused into mechatronics design and actuators control. As far as mechatronic design, much work is devoted to building hydrofoils using, e.g. piezo-electric fiber composite (Ming et al., 2009), embedding SMA wires into an elastic material such as silicone (Wang et al., 2008) or using SMAs as linear actuators (Rediniotis et al., 2002). An important challenge is the control

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[1] Robotuna, a robot fish developed at MIT in 1994, had 2,843 parts controlled by six motors (font: MIT News, http://web.mit.edu/newsoffice/2009/robo-fish-0824.html)

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of such materials. In the case of SMAs, excellent results have been achieved by (Teh, 2008) and (Meier et al., 2009). In this paper, we present our work on a swimming robot, focussing on the control of the SMA-based actuation system.

2 MECHATRONICS DESIGN

Fishes can swim bending their body in such a way to produce a backward-propagating propulsive wave. Such bending comes in different ways. Anguilliform swimmers show a snake-like motion: their body can be divided into numerous segments from head to tail and can reproduce at least one complete wavelength along the body. Conversely, subcarangifor, carangiform and thunniform swimmers only bends the second half of the body (roughly) and the number of segments is reduced to one or two.

For our model, we have chosen to imitate the subcarangiform swimming style because of the reduced number of segments w.r.t. anguilliform fishes, which simplifies the study and the implementation, while having enough degrees of freedom that allow complex motion patterns to be reproduced. Our fish model can also bend the front part of its body, which makes a total of three bendable segments (cf. Figure 1).

The fish is formed by a continuous structure made of polycarbonate 1 mm thick, which represents the fish backbone and spines. This material has been chosen for its temperature resistance, impact resistance and flexibility. Additional supporting structure made of PVC is employed to support the silicon-based skin of the robot. The overall length of the fish is 30 cm (not including the caudal fin). Along the backbone, six SMA actuators are used to bend the body. Their length is $1/3$ body length (i.e. $8.5cm$, not counting the caudal fin and the head) and are positioned in pairs, in such a way to produce an antagonistic movement. Thanks to this arrangement, the body segments can bend up to ≈ 30 degrees. The diameter size of the wires has been chosen as a trade-off between current consumption, pull force and contraction time. We have adopted a SMA with a diameter size of $150\mu m$ that has a pull force of 230 grams, a consumption of 250 mA at room temperature, and a nominal contraction time of 1 second. Such contraction time allows an undulation frequency that is enough for producing motion in water.

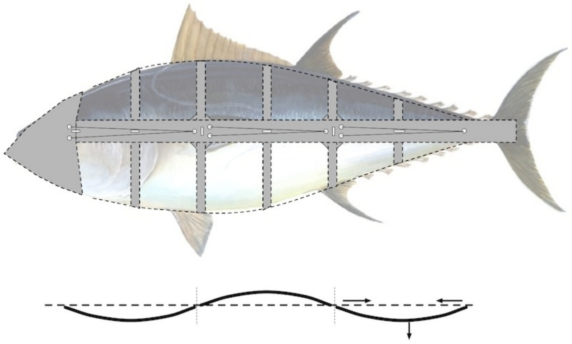

Figure 1: Lateral and upper view of the deformable structure. Note the location of the SMA wires along the body.

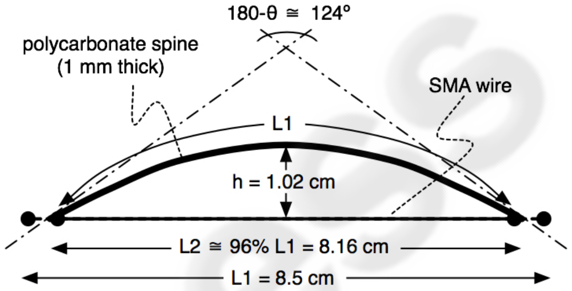

Figure 2: Principle of the bendable structure. The SMA wire is parallel to the spine segment. As it contracts, it causes the polycarbonate strip to bend.

2.1 Shape Memory Alloys

SMAs are materials capable of changing their crystallographic structure (from *austensite* and *marteniste* phases), due to changes in temperature. When an SMA wire is subjected to an electrical current, Joule resistive heating causes the SMA actuator to contract. SMAs have the advantage that they work at low currents and voltages, are extremely cheap and are easily available commercially. Nitinol, one of the most commercially available SMAs, is an alloy of nickel and titanium (NiTi). It is characterized by a high recovery stress ($> 500MPa$), low operational voltage ($4-5\ V$), a reasonable operational strain ($\approx 4\%$) and a long life (up to 10^6 cycles).

The behavior of SMAs is more complex than many common materials: the stress-strain relationship is non-linear, hysteretic, exhibits large reversible strains, and it is temperature dependent. For this reason, a low-level control electronics has to be designed in order to have a position control close-loop precise enough for the application at hand. An important characteristics of SMAs is that they can also be used as sensors. In fact, once heated applying a given current, one can measure their resistance and calculate the actual percentage of shrinking. This measurement can be used as feedback for achieving precise position control.

3 SMA CONTROL

The control accuracy of smart actuators such as SMAs is limited due to their inherent hysteresis nonlinearities (see Figure 3) with a local memory. The existence of minor loops in the major loop because of a local memory also makes the mathematical modeling and design of a controller difficult for SMA actuators. Therefore, to enhance the controllability of a smart actuator, the Preisach hysteresis model (Visintin, 1995) has emerged as an appropriate behavioral model. Nevertheless, the modeling is difficult and the model equation remains complex. So even though this model is commonly used (Choi et al., 2004), the use of a heat transfer model and sensor hardware has also been proposed.

As pointed out earlier, SMAs provide the possibility to develop controller systems without sensor hardware. The detection of inner electrical resistance allows to regulate the actuator movement (Ikuta et al., 1988). The method consists in measuring the electrical resistance of an SMA element (Teh, 2008) as a form of temperature measurement. An advantage of this method is that the hysteresis on the resistance curve is smaller than the hysteresis on the temperature curve, which makes the linear approximation more accurate.

The maximum contraction of the wire can be measured as

$$\Delta L_{A_f} = \frac{R_{SMA_{M_f}} - R_{SMA_{A_f}}}{L_R}, \tag{1}$$

where $R_{SMA_{M_f}}(\Omega)$ is the SMA resistance in martensite finish temperature (relaxed SMA), $L_R(\Omega/m)$ is the linear resistance and $R_{SMA_{A_f}}(\Omega)$ is the resistance at austenite finish temperature (i.e. at maximum contraction).

Figure 5 shows the performance of a mock-up for a current of $350mA$. The angle shown in the figure is in good accordance with the theoretical value of 28° (cf. Figure 2). Note that the wires' speed and strain contraction depends on how fast and by how much the wire temperature is increased. In our tests, we have verified that SMAs wires can be fed with a current of up to $500mA$ without compromising their behavior, achieving faster response and higher percentages of contraction.

3.1 Controller Tuning

In order to tune the control system, we set up a mock-up of a segment of the fish's backbone, corresponding to a $10 \times 2cm$ stripe of $1mm$ thick polycarbonate, with a $174mm$ long SMA wire in a V-shaped configuration, in order to double the pull force (see Figure 4).

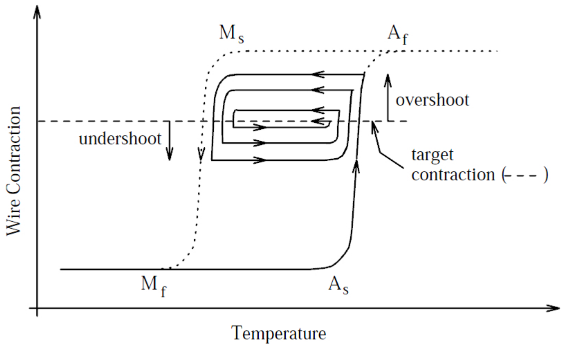

Figure 3: Histeresis of the SMA. (A_s, the austenite start temperature; A_f, the austenite finish temperature; M_s, the martensite start temperature; and M_f, the martensite finish temperature).

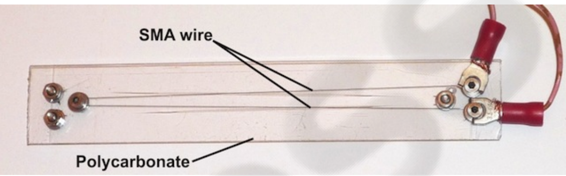

Figure 4: The test mock-up.

For the control, we used a PID (proportional-integral-derivative) controller, which responds to the equation

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}, \tag{2}$$

where $e(t)$ is the signal error and $u(t)$ is the control input of the process. K_p, K_i, K_e are the proportional, integrative and derivative gains. Then by posing $K_i = \frac{K_p}{T_i}, K_d = K_p T_d$, where T_i is the integral time constant and T_d is the derivative time constant, the PID controller can be written in the s domain as

$$U(s) = K_p \left[1 + \frac{1}{T_i s} + T_d s \right] E(s). \tag{3}$$

Following Ziegler-Nichols, we have tuned the values to the three parameters (K_p, T_i, T_d) of the PID controller based on the analysis of the open and close loop of the system to be controlled. The dynamics behavior of the system is defined using the following first-order linear transfer function:

$$G(s) = \frac{K_0 e^{-s\tau_0}}{1 - s\gamma_0}, \tag{4}$$

where the coefficients K_0, τ_0 and γ_0 are obtained from the response of the open loop system to a step input. Starting from the stabilized system at $y(t) = y_0$ to $u(t) = u_0$, a step input is applied from u_0 to u_1.