Preprint of the paper submitted to the 4th IFAC-Symposium on Mechatronic Systems Heidelberg, Germany, September 12th-14th, 2006

MACROSCOPIC SMA WIRE BUNDLE ACTUATOR/SENSOR SYSTEM: DESIGN, MEASUREMENT, CONTROL APPROACH

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Prestrainend shape memory alloys (SMA) change their length when heated above their transformation temperature. Based on this property this paper presents the design of macroscopic SMA actuators scalable in force and length that keeps up a short cool down time to guarantee a high frequency of contraction/stress cycles and the possibility of arranging the fixings in any direction. A new model of the macroscopic actuator has been developed. The model describes the actuator's behaviour and offers the possibility to use the resistance of the actuator as a linear position encoder. Experimental results demonstrate that the newly developed SMA device can be used as actuator and position sensor. The measurement shows that the fixings of the actuator can be shifted or rotated without influence on the actuators behaviour and therefore various uses are possible. Based on the measurement a first control approach has been developed and tested.

Keywords: Actuators, Sensors, Measured values

1 INTRODUCTION

Shape memory alloys (SMA) offer the possibility of new actuator design. The simplicity of their actuation principle and their compatibility have made them attractive for miniaturised and micro-technical systems (Dario, et al., 1997). The SMA-based actuators use the transformation mechanisms known as the one-way shape memory effect. Under certain conditions the shape of the SMA can be deformed up to 8% (in alloys such as Nickel-Titan) (Troisfontaine et al., 1999).

In this paper, the development of a novel *macroscopic* SMA actuator is presented. The actuator is scalable in force and length the fixing can be arranged in any direction.

In general, the material behaviour, i.e. the relation between temperature and length, of shape memory alloys is non-linear and hysteretic, caused by the property of the material. Designing macroscopic SMA actuators necessitates the development of a model that characterizes the nonlinearities and the hysteresis in the used materials. The described solution is an innovative actuator/sensor system on a large scale for applications containing a high power-to-weight ratio. In addition, the new model allows using the actuator as a linear position encoder and force sensor at the same time. Combining single SMA wires as in a biologically inspired muscle results in the new actuator. Using two of these actuators as flexor/extensor offers the possibility to generate a defined force at every time. The paper deals with the description of the SMA actuator developed. An experimental setup has been designed to develop the model for the control approach. After a presentation of the measured data the experimental results are presented.

2 ACTUATOR DESIGN AND CONTROL APPROACH

The design of a macroscopic SMA actuator has to deal with the time needed for one contraction/stress cycle.

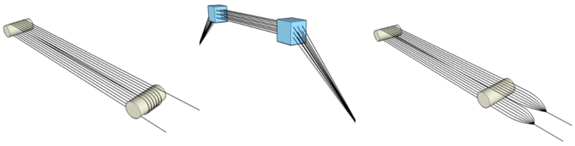

Fig. 1 Three possibilities of combining thin wires to one actuator. From left to right: one long wire wrapped around the mounting parts; wires only connect in parallel; a parallel-serial connection

An SMA element is usually heated by passing an electric current through it and cooled by the heat transfer to the environment.

2.1 Design of the actuator

The force of a SMA-wire is proportional to its diameter. By using only one wire to provide a high force, the cycle time highly increases with the wire's diameter.

One way to solve this problem is the combination of a multitude of thin wires to one actuator. By keeping a distance between each of the single wires, the cool-down time of the thin wires can be held up for the entire actuator. This is realized by tapping a plastics cylinder and wrapping it around the wire. In this novel way, a constant distance between all wires is realized and, in addition, the cylinder is used as a mounting part for the actuator.

Another advantage of this new design is the scalability of pull force and length. The pull force depends directly on the amount of wires. The actuator we use for our measurements is made of 10 pairs of SMA wires with a thickness of 100μm and 180gf pull-force each. The total pull force of one bundle is 3.6kgf. The actuator has a length of 22cm and a maximum displacement of 1.5cm. To hedge against material inhomogenities the parallel-serial connection type of construction is used.

The bus bar is only on one mounting part and there is no need for separators to prevent the wires from making physical (electrical) contact with their neighbours on the same side in the event they go slack, as it is needed for example by connecting one wire in serial.

2.2 Control approach of the actuator

The macroscopic use of SMA-actuators need a complex nonlinear control approach. Theories used are: neural fuzzy, dissipativity, variable structure control and segmented binary control (Kumagai, et al., 2000; Gorbet and Wang, 1998; Grant and Hayward, 1997; Cho and Asada, 2005).

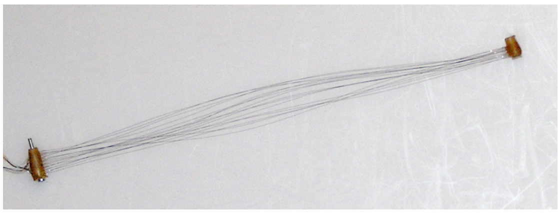

Fig. 2 Picture of the actuator

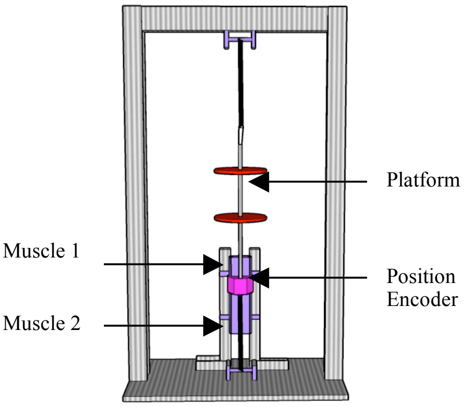

Fig. 3 CAD model of the experimental rig

The novel control approach that we have developed is based on the hypothesis of a decreasing resistance of the actuator during contraction. Based on this, the resistance can be used as a linear position encoder. Thus there is no need for external sensors.

The resistance can also be used for an optimal heating and to prevent overheating and thereby burn out of the actuator (Featherstone and The, 2004).

The amount of current needed to contract the actuator gives information about the pull-force.

3 EXPERIMENTAL HARDWARE

The experimental rig is shown in Figure 3. It consists of an actuator fixed in the center of the top bar. A platform to place different weights is base-fixed at the actuator followed by an inductive linear position encoder used for evaluation of the resistant-based position encoding. There is the option to fix a second actuator from the bottom of the rig to the position encoder.

A regulated power supply is provided by the use of a pulse width modulation. It makes five different constant currents available. An integrator is upstreamed the signal digitalisation. All real-time computation and data capture functions are performed on a ME-RedLabs 1608FS board from Meilhaus Electronic.

All measurement data relate to an actuator that is 22cm long and contains 10 pairs of wires with a pull force of 3.6kgf.

4 EXPERIMENTAL RESULTS

All measured data contain voltage, current and resistance of the actuator and its position (measured by the inductive linear position encoder) in subject to different weights and currents.

4.1 One actuator loaded with different weights and currents

At first the actuators is loaded with weights between 250g and 2000g in steps of 250g. At each load the current varies between 200mA and 2000mA.

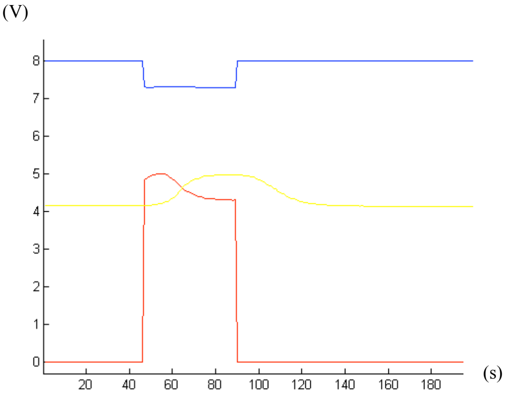

Fig. 4 Sample of the measurement of contraction (middle line; 1V = 10mm), voltage (bottom line) and current (upper line; 1V = 1A)

A representative example of the actuators behaviour is shown in Figure 4. This graph shows the contraction curve of the actuator under two different load conditions. The total contraction is independent of the load condition, but the time needed to contract varies with the load. The contraction cycle starts at an exciting current of 250mA; a higher current leads to a shorter contraction time. There is a high delay recognizable between applying the current and beginning of the contraction.

4.2 One actuator loaded with different weights and currents and a continuous pre-heating current of 200mA

To reduce the delay between applying the current and the actuators contraction the actuator has a continuous current of 200mA which leads to a pre-heating of the wires. This results in an offset next to the austenite start temperature (Fig. 5). Similar to the first measurement the actuator is loaded with weights between 250g and 2000g in steps of 250g and at each load the current varies between 200mA and 2000mA. In this case the actuator reacts more direct to the applied currents.

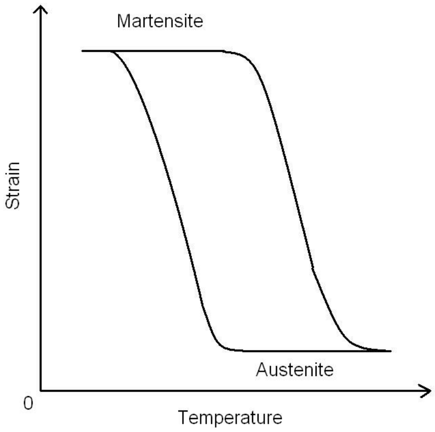

Fig. 5 principle Strain/Temperature diagram (according to Massad, 2003)

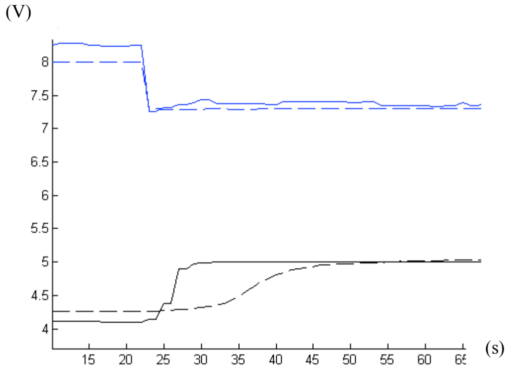

Fig. 6 Reaction of the actuator with (solid line) and without (dashed line) a continuous pre-heating current of 200mA

4.3 Dynamic behaviour

For an optimal control approach the dynamic behaviour of the actuator is important. Therefore the current is changed after half the way of the contraction and replaced by a higher or lower current. The analysis of the measurement shows that the resulting contraction curve is similar to the combination of the curves that were measured by applying only the higher or the lower one (Figure 7).

4.4 Shifted/Rotated fixing of the actuator

To arrange the fixing anywhere there is a need to look at the behaviour of the actuator with shifted/rotated fixing. The results of the measurements show, that twisting the fixing up to 90° does not lead to different actuator behaviour. As well it is possible to shift the fixing up to a difference up to 50mm. The elasticity of each single wire compensates the different strains of the whole actuator. This experiments show that the actuator can be used to generate rotary motion.

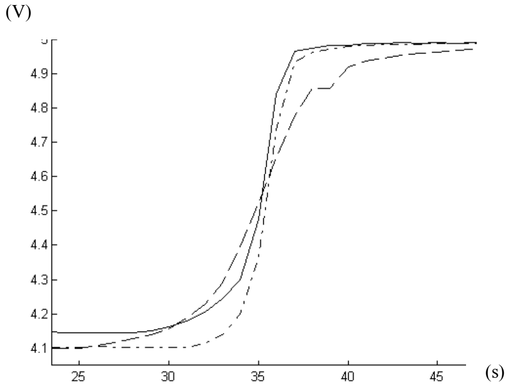

Fig. 7 Contraction (solid line; 1V = 10mm) of the actuator by varying current according to constant power delivery (dashed lines; 1V = 10mm).

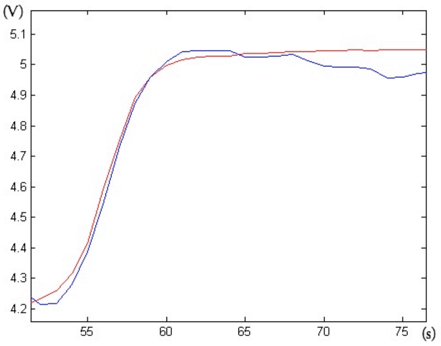

Fig. 8 close connection between resistance (scaled by Equation 1) and contraction (1V = 10mm)

4.5 The Resistor as a Linear Position Encoder

The main problem of SMA actuators is moving toward a certain position. Heating the actuator with an electric current causes a fast contraction that differs with the payload. To get a certain position necessitates to know the payload exactly or to measure to contraction with a position encoder. More efficient than an external sensor is the use of the resistance of the actuator as a linear position encoder. Therefore the change of the resistance is compared to the contraction.

Figure 8 shows the close connection between resistance and contraction at 1750mA and a load of 1750g . 1V is equivalent to a contraction of 10mm. To implicate resistance and contraction equation 1 is used.

Equation 1

$c = -0.15r + 9.1$

c = contraction and r = resistance.

Table 1 Selection of sample measurement data

mA	250gf	1000gf	1750gf
1000	-2r + 12.3	-2r + 12.2	-2r + 12.2
1250	-0.8r + 10.45	-0.8r + 9,9	-0.8r + 10
1500	-0.5r + 11.2	-0.5r + 11.2	-0.5r + 11.2
1750	-0.1r + 9	-0.15r + 9.1	-0.15r + 9.1

The results (Table 1) show that the connection between resistance and contraction is independent of the load and depends only on the applied current. The interrelation between current and resistance is linear and can be retrieved easily. The total change of the actuators resistance between both states is 0.711Ω and the values can be reproduced to a deviation of 0.002Ω

5 CONCLUSIONS AND FUTURE WORK

This paper has described a method to build a scalable macroscopic SMA actuator with the possibility of variable fixing. It involves measuring the electrical resistance, calculating an interrelation to use the actuator as a linear position encoder as a function of the measured resistance and the applied current parameters. In addition, the applied current provides information about the generated force of the actuator.

The paper has described a method to combine a multitude of SMA wires to one actuator and demonstrate the effectiveness of this new method in relation to future applications.

Although it has been successfully shown that an SMA actuator on a large scale can be used as a linear position encoder, an optimal control approach has yet to be developed. Therefore additional experiments are necessary.

The first approach to control the actuator is to use a pulse-width modulation triggered by the resistance of the actuator. Till the target resistance value is reached, a current is applied to the actuator. At this point the current is cut of until the resistance reaches a value larger than the target resistance. According to the interial behaviour of the actuator it should be oscillating around the target contraction point.

To move the actuator to a certain position necessitates the use two actuators in a flexor/extensor manner. This offers the possibility to generate a defined force at every point of contraction. The force can be controlled by the provided amount of current and the resistance which provides position. The next measurement will define the retaining current of the actuator and will thereby be the missing link to complete the control approach.

Envisioned application is the actuation of a humanoid robot. First numerical models have been established and the robot has been built (Figure 9).

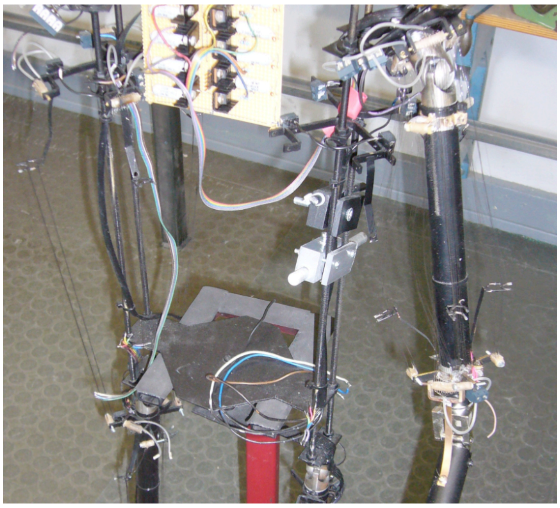

Fig. 9: Envisioned application in a robotic arm joints actuation.

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