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Design, Measurement Experiments and Application of a Macroscopic Shape Memory Alloy Actuator System

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Abstract:
Prestrainend shape memory alloys (SMA) change their length when heated above their transformation temperature. Based on this property various micro-technical actuators have been developed in the past. This paper presents the design of novel macroscopic SMA actuators scalable in force and length. Our design approach allows arranging the point of actuation in any direction and ensures a short cool down time to guarantee a high frequency of contraction/stress cycles. The use of the new actuator also necessitates a novel control approach. A model to describe the actuators behavior has been developed and experimentally validated. It offers the possibility of using the resistance of the actuator as a linear position encoder and provides a basis for the control approach of the actuator. The application to a new bipedal walking robot demonstrates one envisioned future use of the actuators. One advantage over electric motors lies in the large variety of user-defined points of actuation of the scalable actuators on a mechanical structure. This allows generating joint movements without the common restrictions holding for electric motors on the possible point of actuation.

Keywords: macroscopic SMA actuator, SMA wire bundle actuator, robotic actuator

Introduction

Shape memory alloys (SMAs) offer the possibility of new actuator design. The simplicity of their actuation principle with respect to the relatively large forces generated and their (bio)compatibility with other material have made them attractive for miniaturised and micro-technical systems [1]. Prestrainend SMAs change their lengths up to 8% when heated above their transformation temperature [2]. Based on this property various micro-technical actuators have been developed [3,4]. In this paper, the development of a novel *macroscopic* SMA actuator is presented. The actuator is scalable in force and length and allows the point of actuation to be arranged in any direction.
In general, the material behavior 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 design approach described in this paper is an innovative, macroscopic actuator/sensor system for applications with 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.

Actuator Design

The maximum force of a SMA-wire is proportional to its diameter. If only one SMA wire is used to provide a high force, the cycle time highly increases with the wire's diameter. The new actuator/sensor design presented in this paper combines many single SMA wires in a new way to one muscle-like actuator with a high possible field of application as the primary object target. By keeping a minimum distance between each single wire, a short cool-down time of the thin wires can be ensured for the entire actuator.
Commonly, the construction of the SMA wire bundle consists of a multitude of wires in parallel attached to a bracket by crimps at the both ends of the actuator (Fig. 1). This should preserve the contraction properties of the wires [5]. One way to raise the pull force of the actuator is the combination of wires with different diameters [6]. The bundles are attached to the device with a cable at both ends. One end is moveable and one stationary to move the device. This sort of devices have circuit points at both ends of the actuator and the mounting is space consuming because of the minimum distance needed between the bracket, the cable and the device.
To advance the actuator design the objective is to develop a space-saving actuator with circuit points only on one side and a novel fixing that is integrated in the actuator to provide the possibility of rotating. The actuator should realize a parallel-serial connection of the wires instead of connecting the wires in parallel only to reduce the current needed for contraction.

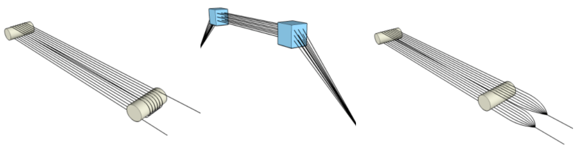

***Fig. 1:** The three investigated possibilities of combining thin wires to one actuator. Left: one long wire wrapped around the mounting parts. Middle: wires only connect in parallel. Right: a parallel-serial connection*

Tapping a plastics cylinder and wrapping around the wire is one way to realize this sort of connection. 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. For mounting the actuators at the device a U-shaped profile is used and a hole is drilled into the cylinder for combining bracket and fixing with a stick. This also allows the actuator to rotate within the fixing.
The bus bar is only on one mounting part and there is no need for additional separators to prevent the wires from making physical (electrical) contact with their neighbors on the same site in the event they go slack, as it is needed for example by connecting one wire in serial (Fig. 2).
By using this actuator design the amount of wires and therefore the current needed is halved compared to the only-parallel actuators and thereby the diameter of power supply cables can be reduced.
Using two of these actuators in an antagonistic flexor-extensor muscle-like manner offers the possibility to generate a defined force at every time.
Another advantage of this new design is the scalability of pull force and length. The pull force depends directly on the number of wires. One type

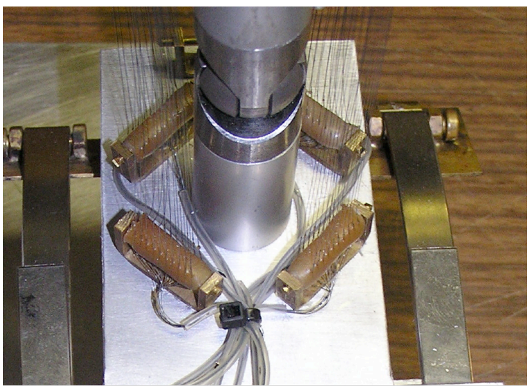

***Fig. 2:** Example of the actuator and its fixing*

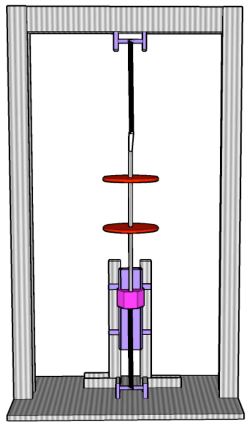

***Fig. 3**: CAD model of the experimental rig*

of actuator used is made up of 10 pairs of SMA wires with a thickness of 100µm and 180gf pull-force each. The total pull force is 3.6kgf. The actuator has a length of 22cm and a maximum displacement of 1.5cm.

Experimental Hardware and Measurement

The macroscopic use of SMA-actuators needs a complex nonlinear control approach. Theories used are: neural fuzzy, dissipativity, variable structure control and segmented binary control [7-10].
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 or even burn out of the actuator [11].
The amount of current needed to contract the actuator gives information about the pull-force
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. 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.

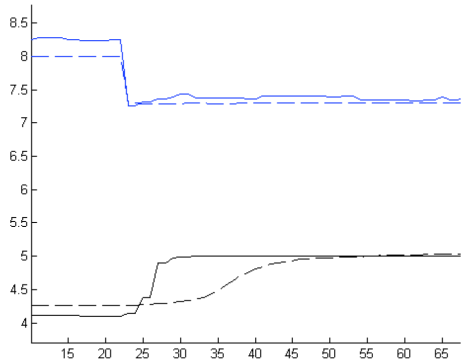

Fig. 4: *Reaction of the actuator with (solid line) and without (dashed line) a continuous current of 200mA*

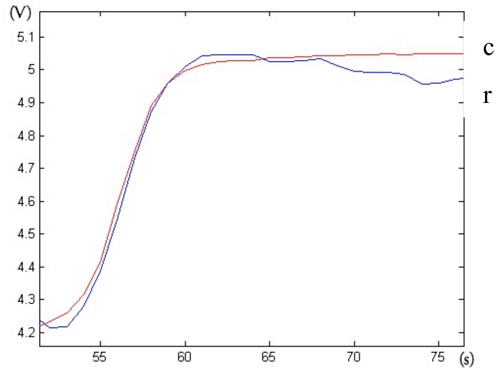

Fig. 5: Close connection between resistance (r) and contraction (c) [10mm/V]

All measurement data relate to an actuator that is 22cm long and contains 10 pairs of wires with a pull force of 3.6kgf.
All measured data contain voltage, current and resistance of the actuator and its position in subject to different weights and currents. To reduce the delay between applying the current and the actuators contraction the actuator has a continuous current of 200mA. This results in an offset next to the austenite start temperature. 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 the case of a continuous current (Fig. 4), the actuator reacts more direct to the applied currents.
To arrange the fixing anywhere there is a need to look at the behavior of the actuator with shifted/rotated fixing. The results of the measurements show, that twisting the fixing up to 90° does not lead to a different actuator behavior. 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.

Control Approach

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 the contraction with an external 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 has to be compared to the contraction.

Figure 5 shows the close connection between resistance and contraction at 1750mA and a load of 1750g. 1V is corresponds to a contraction of 10mm. To relate resistance and contraction the following equation is used

$$c = -0.15r + 9.1$$

where 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 given in Table 1 strongly indicate that the relation between resistance and contraction is independent of the load and depends only on the applied current. The interrelation between current and resistance is linearly and can be obtained easily from measurements and data fitting.

Application

An application envisioned for demonstration of the new actuator/sensor design is the actuation of the legs of a humanoid robot. First simulation models of the new actuator and of the multi-body dynamics of the robot legs consisting of 6 actuated joints have been established and a first prototype of the bipedal robot has been built (Fig. 6). At first a skeleton of two legs and a hip has been built providing the needed degrees of freedom for bipedal walking. Thirteen actuators haven been arranged in each leg for this purpose. The arrangement of the points of

Fig. 6: *CAD model of the robot (left) and robot prototype (right)*

actuation has more freedom for the new SMA actuator than for electric motors that are placed in the actuated joints in almost all currently successfully walking humanoid robots. In addition the novel actuator system enables a more lightweight robot design. Furthermore, if new requirements are given for the actuation of a certain robot joint either one of the existing actuators can be changed or an additional actuator can be added easily.

Conclusion and future work

A novel SMA wire bundle actuator has been designed and implemented. Its properties have been measured and investigated in experiments. It provides a large possible field of application and it is being applied a bipedal walking robot. A phenomenological model has been derived describing the connection between resistance and contraction. Based on this model a control approach has been established. As first realized motion the robot is able to stand on one leg and kick a ball. It is planned to realize the already simulated bipedal walking motion in experiments with the physical prototype.

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