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Novel Characterisation and Modeling of the Thermal Behavior of Multi-Wire SMA Actuators for Robot Grippers

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Summary: This study describes the behaviour of a multi-wire shape memory alloy (SMA) actuator, with the bending angle expressed as a function of the actuator surface temperature. The temperature behaviour is quantified based on data obtained from an infrared sensor, and the hysteresis behaviour of the SMA actuator is modelled applying a sigmoid function. The least squares method is employed to identify the parameters of the sigmoid function, thereby enabling the positioning of the actuator with an average deviation of 0.5°. These results provide a foundation for position control in SMA-based robotic grippers.

Keywords: shape memory alloy, nitinol, actuator, surface temperature, robot grippers

Introduction and Motivation

Shape memory alloys (SMAs) are among the so-called 'smart materials' that have been identified by researchers as a potential avenue for application in the field of robotic grippers [1], [2]. The thermal activation of SMA can result in a change in shape between two states, a phenomenon known as the 'two-way' effect. This change is based on a transformation in the crystal structure between the martensite and austenite states [3]. The application of SMA as actuators provides a more compact alternative to servomotors, which are characterised by high volume and weight [4].

One challenge to the widespread adoption of SMA actuators is their restricted force output. While thicker SMA wires do result in an augmented force output, this also leads to an extension of the already considerable cycle time. This restricts their viability for incorporation into robotic applications [4]. Determining the position of the SMA actuators represents a challenge due to the temperature-dependent hysteresis. This can only be addressed through approaches such as the Lagoudas or Souza-Auricchio model [1], [4].

In this paper, the existing knowledge regarding the temperature-dependent deformation of SMA is applied to a SMA multi-wire actuator. This study examines the bending angle of a SMA multi-wire actuator in relation to the surface temperature of the SMA multi-wires. This provides a new foundation for control or determination of the opening angle in robot grippers, which has the potential to advance SMA technology in industrial robotics.

Methods

In order to enhance the output force without significantly extending the cycle time, a SMA actuator with a parallel configuration of four Nitinol wires with a diameter of 0.5 mm is employed. The output force increases in proportion to the number of wires up to a maximum of 7 N at the actuator edge [4], [5].

The temperature of the SMA wires is controlled by a pulse-width modulation (PWM) signal, which ensures that a predefined shape, specifically a designated angle, is attained. The surface temperature is monitored with an infrared sensor, and the heating power is adjusted based on the temperature to achieve the desired angle. Fig. 1 illustrates the measurement setup.

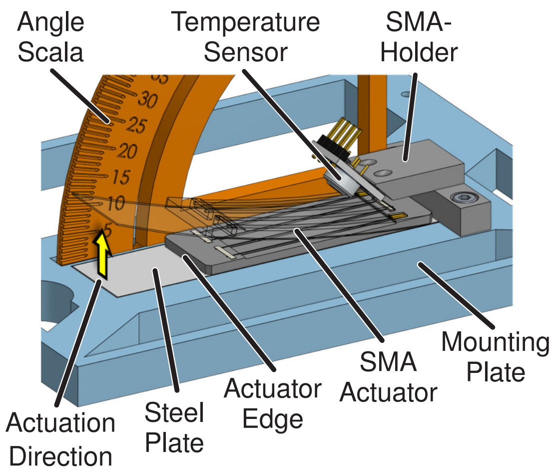

Fig. 1: Measurement setup

The COMPAKTIV 3920H is employed as the SMA actuator. It is fastened to one side and mounted on a steel plate. The Hailege MLX90614 infrared sensor is utilised as the temperature sensor. An Arduino MEGA 2560 is employed to controll the SMA. The actuator is supplied with a maximum current of 3 A.

Results

The thermal behaviour of the actuator surface was investigated experimentally, whereby the surface temperature was increased from 23 ℃ to 85 ℃ in 1 ℃ increments. The bending was recorded (see Fig. 2 Meas. heating/cooling). The maximum temperature of 85 ℃ was selected because it corresponds to the maximum bending of 20° after the permissible excitation time. The hysteresis behaviour of Nitinol can be simplified through the use of sigmoid functions. If the parameters of the function are based on the data sheet of the SMA multi-wire actuator, the observed behaviour, and a review of the relevant literature [1], [6], the experimental results are not described well (see Fig. 2 Calc. heating/cooling).

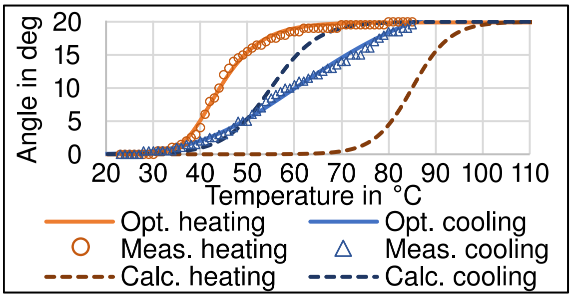

Fig. 2: Hysteresis of SMA actuator surface temperature with sigmoidal modeling

The study by Kciuk et al. provides a description of the SMA hysteresis behaviour, which offers a reference point for further analysis. The adapted formula for calculating the bending angle $\alpha_{bending}$ as a function of the surface temperature (T) is presented below [6]:

$$\alpha_{\text{bending}}(T) = \frac{\alpha_{\text{max}}}{((1+\exp(-\beta\cdot(T-T_0)))^n} \quad (1)$$

In accordance with the results of the measurement, the least squares method, as outlined by Kciuk et al., is applied to ascertain the parameters α_{max} (max. bending angle), β (max. slope of the hysteresis curve), T_0 (the mean of the start and end surface temperatures of a phase transition) and n (exponent for curve asymmetry, limited to 10 to prevent overfitting). The start and end points were given more weight to ensure consistency during cooling and heating. The results are shown in Tab. 1.

Tab. 1: Optimised parameters

Parameter	Heating	Cooling
α_{max}	19.9°	26.1°
β	0.17 1/℃	0.05 1/℃
T_0	28.87 ℃	16.46 ℃
n	10	10

The overall RMSE is 0.5° (see Fig. 1 Opt. heating/cooling).

Discussion

The position of a multi-wire SMA actuator can be determined by measuring the surface temperature using an infrared sensor and creating a model with an average deviation of 0.5°. A sigmoid function can be employed for the purpose of providing a simplified mathematical description of the angle change. The parameterisation of this function can not be based on standardised or manufacturer-provided data, as the measured surface temperature differs from the wire temperature. Apart from a shift in the temperature, the heating curve exhibits a similar shape (see Fig. 2 Opt./Calc. heating). The discrepancies observed in the cooling curve at temperatures exceeding 55 ℃ can be attributed to the non-linear hysteresis exhibited by the material and the spring-like behaviour of the steel plate. The parameters in Tab. 1 apply from 23 ℃ to 85 ℃. It is necessary to recalculate the parameters for each distinct configuration of the SMA actuator.

Conclusion

The study demonstrates that the actuation angle of a multi-wire SMA actuator can be determined by a sigmoid function based on the surface temperature. This finding provides a basis for the position control of SMA-based robot grippers.

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