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Modeling and Control of Shape Memory Alloy Spring Actuator in a Flexible Tube Manipulator

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Abstract

The paper describes the modeling and positional control of a flexible tube manipulator intended for medical applications. The flexible tube is made of silicon rubber material and its tip is controlled via a Proportional Integral Derivative (PID) controller. The configuration is made compact with Shape Memory Alloy (SMA) spring as the prime actuator. The spring manipulates the flexible tube in the austenite phase and the amount of current required to control the spring is delivered via the controller. A single SMA spring can provide actuation in one direction and it returns to its initial position on sufficient cooling. To counter the slow response nature of SMA material, a bias spring is placed parallel to the SMA spring which brings the SMA spring to its initial position in a fast manner during the cooling phase. This paper presents the constitutive model of SMA-bias spring pair along with the development of PID controller, where the control objective is the point to point (PTP) positional control of the manipulator tip. The PID controller results demonstrated a satisfactorily positional tracking ability with the SMA actuator.

Keywords: SMA actuator; Flexible tube manipulator; PID controller

Introduction

The incorporation of flexibility in medical robots has resulted in collision-free systems that are not restricted in grasping things with their end effectors only but with their body also. They have a continuous form of appearance, hence the name continuum. This continuum robotics concept has been introduced mechanically in three forms: (a) tendon based designs, (b) concentric tubes based designs and (c) locally actuated backbone designs. In the third form, the most commonly found are shape memory alloy actuators. SMAs have been in the market for the past few years, though they were first introduced as actuators in 1984 by Honma et al. in Japan [1]. Since then, many researchers have proposed their use in endoscopic applications. Apart from their use in endoscopes, now they are quite popular in the medical community as their use has been reported in laparoscopy, colonoscopy, colorectal surgery, neurosurgery, urology, etc. In this paper, the basic idea is implemented with SMA spring as actuator and a steel bias spring to provide bias force on SMA spring. A constitutive model of SMA-bias pair is discussed and the PID controller is applied for point to point positional control of the tip of the flexible tube manipulator.

Design

The proposed mechanical flexible tube manipulator consists of a silicon tube of 100 mm length and 15 mm diameter as a primary flexible body, as shown in Figure 1. Two spacers are placed along its length to accommodate two springs longitudinally with one spring as SMA spring and another spring being a normal bias spring. The springs are placed in the opposite direction to each other so that if one produces bending in the left direction then the other can bring it back to its initial direction. As SMAs have this unique feature to regain their original shape on heating, we have used this property to provide actuation. When one spring is heated, it contracts and due to resistance offered by the spacers to full contraction, spring regains only some portion of its total length depending upon the voltage pattern and thus a recovery force is generated which ultimately produces a bending moment about a plane. The magnitude of the heating force is high enough when compared to the resisting spring force offered by the other spring. When the current gets off, the other spring provides the bias force and brings back the tube to its original position.

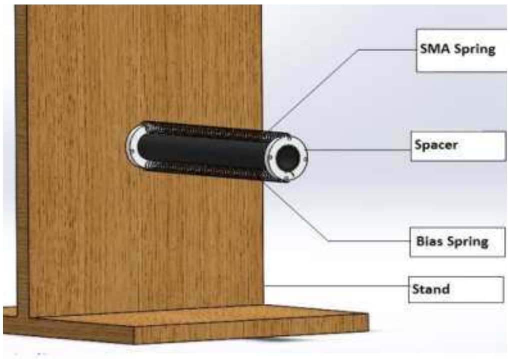

Figure 1: CAD model of flexible tube manipulator

Table 1: Properties of SMA spring

Parameter	Symbols	Material Phase	Units	Value
Start temperature	M_s	Martensite	°C	58
	A_s	Austenite	°C	60
Finish temperature	M_f	Martensite	°C	45
	A_f	Austenite	°C	75
Modulus of rigidity	G_M	Martensite	MPa	15120
	G_A	Austenite	MPa	31840

Mathematical Model

The SMA spring can be deformed below or in its martensite temperature i.e. at room temperature. When heated with an electric current, also known as electrical/Joule heating, it contracts and tries to regain its original shape on reaching to its austenite phase. In Joule heating, the relation of an applied voltage and SMA temperature could be stated as (1):

$$T_i(t) - T_{amb} = \frac{V(t)I(t)}{hA_c}\left(1 - e^{-\frac{t}{t_h}}\right) + (T_{ini} - T_{amb})e^{-t/t_h} \quad (1)$$

The force-deflection relation of the SMA actuator can be estimated from the (2), if the temperature is known at a given instant. In an SMA and bias spring pair, the force function could be stated as

$$f(F_i) = C_1(F_i - F_o) + C_2G(C)\left(\frac{F_i - F_o}{K_s}\right) + C_2\delta_l G(\xi)(\xi_{si} - \xi_{so}) \quad (2)$$

The force at any instant can be predicted by using an iterative method like Newton-Raphson for a known value of temperature with properties as shown in Table 1.

Results and Discussion

When PID control is applied on SMA bias spring pair (as shown in Figure 3) with $K_P = 20; K_I = 0.01; K_D = 0.002$, the maximum overshoot among multiple set points is around 58%. The force is a function of martensite fraction (ξ) which varies with temperature, as shown in Figure 2. Initially, ξ is 0.32 which remains the same till it reaches its preloaded A_s^* that is around 66°C for a preload of 64.26 MPa. When reaches its austenite phase, the force starts to increase. When ξ becomes zero on reaching preloaded A_f^* of around 81°C, the force reaches its maximum of 3.86 N.

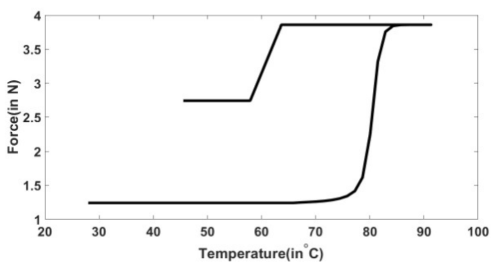

Figure 2: Force variation with temperature

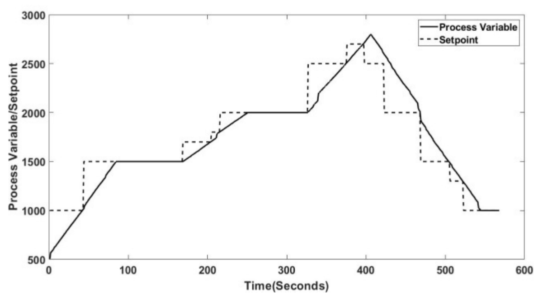

Figure 3: Tracking of setpoint profile with PID

References

[1] D. Honma; K. Miwa and N. Iguchi.: Application of Shape Memory Effect to Digital Control Actuator. Japan Society of Mechanical Engineers, Vol. 27, No. 230, pp. 1737-1742, 1984.