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Developing a novel continuum module actuated by shape memory alloys

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ABSTRACT

Developing continuum manipulators is very useful for special robotic applications. One of the practical usages is medical tools such as endoscope or colonscope. In such applications, a maneuverable thin and flexible manipulator is highly required. In this paper, a basic module is designed which can be used as an element of a continuum manipulator in a modular configuration. Furthermore, the module can simultaneously be utilized both as a joint and actuator in a mechanism. In the structure of the module, three springs of shape memory alloy (SMA) are uniformly distributed and mounted around a bias spring with an angle of 120°. Stimulating SMA springs individually or together provides different rotation regimes. Brinson model and normal compression spring behavior are used for modeling of SMA and bias spring, respectively. Afterward, the model of SMAs and bias spring are integrated to describe the behavior of the actuated module. The modeled module is simulated in Matlab software by which the proper control strategy can be designed. Due to the complex and nonlinear behavior of SMAs, design an appropriate control scheme is a real challenge. In this paper, a new control strategy is developed for regulating a desired position for the two degrees of freedom actuator module. Through the provided test bed, the performance of the strategy is verified. The results present a reasonable performance of the controller and reveal the merits of the developed module in continuum robotic manipulators or flexible joint actuator.

1. Introduction

Continuum manipulators would be used for special applications like endoscopy. Researchers are developing new tools of endoscopy which are miniature and flexible enough to move easily in a limited space. Furthermore, high accuracy, reliability and suitable control mechanism prevents them to damage the flesh of the body [1]. Thus, the mechatronics technology has tried to develop small-scale catheters to ease the entrance of the endoscope to the internal human limb. In conventional endoscopes, the head is bent by control cable which could be very painful for the patient since controlling is hard to achieve.

With the advent of shape memory alloy (SMA) as a smart material, the endoscope tools developed through the new era. As these materials recover their initial shape after heat transfer, they can provide high distortions, and can deliver high force to weight ratio. Additionally, they require low initial driving voltage, have high biological adaptability, and contain uniform and soundless performance, which are thoroughly valuable in medical applications.

SMA presents two major behaviors: shape memory effect and super elasticity. In the first one, when the low temperature material is shaped, recovers the initial shape after heating. While in the second behavior, material accepts a big elastic returnable deformation under loading [2].

Based on aforementioned properties, the SMA is suitable choice for tiny catheters' actuators. Mineta et al. fabricated a guiding wire including a special SMA attached to a spring providing bias force [3]. Lantigineh et al. fabricated a mechanical arm with a worm like architecture which was actuated and controlled through a series of independent structures [4]. They embedded three SMA actuators symmetrically distributed in the sections of the structure. Opposite force in this system provided by compressed air and stimulation was through warm/cold air. Minita et al. [5] fabricated a special actuator and bias spring from a SMA sheet through electrochemical h-pulse method and used that to shrink and bend catheter tip. Jayender et al. attached three wires around the catheter to guarantee the bending in all directions [1]. They also used force algorithm to prevent damage to the body flesh. Pierse presented two mechanisms to facilitate 180° turn of endoscope tip [6]. In the first mechanism, a modular actuator with a few nuts fabricated.

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Nomenclatures

ρ	Module curvature radius
θ_x	Rotation of end plate arround x direction
θ_y	Rotation of end plate arround y direction
θ	Angle of module figure in xy plane from x
φ	Coordinate of module deformation
σ	Stress
τ	Shear stress
ξ	Martensite fraction
ε	Strain
γ_{SMA}	Shear strain of SMA
γ	Shear strain of bias spring
r	Projection of module in xy plane
r_i	i^{th} SMA location in the module cross section
T_i	Temperature of i^{th} SMA
x	Coordinate of end point position
y	Coordinate of end point position
z	Coordinate of end point position
Y	Length variation of SMA spring
F	SMA force
Ω	Phase transformation contribution factor
Θ	SMA spring thermal expansion factor
G	Shear elestic modulus
E	Young elestic modulus
k_1	Coefficient conversion of length to force in SMA spring
k_2	Coefficient conversion of martensite fraction to force in SMA spring
d_{SMA}	Diameter of SMA spring wire cross section
D_{SMA}	Diameter of SMA spring coil
N_{SMA}	Number of coil in SMA spring
δ	Axial length variation in bias spring
δ_θ	Boundary layer arround θ
δ_φ	Boundary layer arround φ
T	Torsional moment in wire section of bias spring
M	Bending moment in wire section of bias spring
M_{SMA}	Bending moment produced by SMAs
M_b	Bending opposig momnet produced by bias spring
α	Angular location of a typical cross section in a coil of bias spring
β	Cordinate for angular position of bias spring elements
η	Cordinate for angular position of bias spring elements
γ_{SMA}	Shear strain of SMA spring
γ	Shear strain of bias spring
r_s	Radius of bias spring wire cross section
R_S	Radius of bias spring coil
N	Number of coil in bias spring
d	Diameter of bias spring wire cross section
D	Diameter of bias spring coil
J	Polar moment of inertia of bias spring wire cross section
I	Moment of inertia of bias spring wire cross section
k	Bending stiffness of bias spring

The nuts turn 90° relative to each other. In the second one, they fabricated an actuator with huge movements and a planetary gear mechanism to provide continuous displacement control. In both works, SMA was used as the actuator. Abadie et al. made a micro actuator using SMA for endoscope which applies Peltier effect for cooling [7]. A miniature catheter, based on SMA actuators, has been designed and fabricated by Dong et al. [8]. It contains a stainless steel liner coil which has been connected to SMA actuator using the nickel electroplating and acrylic resin electrodeposition. However, no method to control the developed active catheter has been proposed. In [9], a novel design has been presented for continuum robots using the compliant joints. Specifically, it has been shown that employing the proposed structure leads to minimizing the twisting angle along the backbone. However, the considered actuators are not SMA. Additionally, no automatic control algorithm has been presented to regulate the robot motion.

Sars et al. presented two practical methods to stimulate the endoscope [10]. First method consists of a two Degrees Of Freedom (DOF) endoscope with four shape memory wires which are located oppositely two by two. In the second method, structures containing an optimized SMA were used to connect to make a modular set. Chapelle introduced a mechanical system with a tube-like configuration in which modules are connected to each other through pin pivots [11]. Each pivot between two modules provides one DOF relative motion, actuated through antagonistic SMA actuators. To reveal the contact with the environment, pressure sensors are used on the pivots of the endoscope. Mensiasi reported a semi-automatic robot for colonoscopy [12]. Her main objective was to use the force of the robot itself rather than external force required to move it. Guiding the endoscope head is provided by three SMA springs located in a container.

Modeling of flexible rods actuated by embedded SMA is also investigated. Lagoudas and Tadjbakhsh [13] developed a model for active flexible rods actuated by SMA. Using this model, Kai and Chenglin explored the application of entirely-integrated Spatial-bending SMA actuator [14].

Control of SMA actuated systems has been a challenge for the researchers. Due to nonlinear and non repeatable behavior of SMA, non-model based control approaches are more usual and applicable than the model based ones, [15]. Additionally, many states of system should be measured or estimated for implementing state based feedback control schemes.

In the presented works of continuum manipulators such as endoscopes and active catheters, although SMA actuators are applied, exact control of these devices have not well been demonstrated. Also, in the case of implementing previously proposed control strategies, a complex sensory system and calculation platform are required. In this paper, a controllable continuum module actuated by SMA springs is developed using a mechatronics novel design, and to regulate its shape, a novel control algorithm is suggested.

The rest of the paper is organized as follows. In Section 2, the details of the module design will be elaborated. The Composite modeling of the module actuated by three SMA springs is investigated in Section 3. In Section 4, the model is simulated which is then employed to develop a position control strategy in Section 5. In Section 6, an experimental test bed is established to verify the developed model and control approach. In Section 7, the computer simulation and real world experimental results are presented. The paper ends with some concluding remarks.

2. Module design

Basic structure of the module is a compressive spring. Three SMA springs are mounted around that to provide a differential actuating system for the module and to produce any desired spatial shape. A set of discs are arranged to be mounted on the module to keep a constant space between bias spring and SMA actuators during the movement, see Fig. 1. The bias spring is placed in the central hole of discs and SMA springs are passed through three other holes of the discs. The empty space of the bias spring lets electrical wires