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Research paper

Modeling of grasping force for a soft robotic gripper with variable stiffness

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ABSTRACT

The purpose of this research is to present a grasping force model for a soft robotic gripper with variable stiffness. The soft robotic gripper was made of shape memory alloys (SMAs) with contraction and variable stiffness properties. A variable stiffness mechanism with embedded sets of SMA fibers was developed; however, the response characteristics of its backbone did not comply with the constant-curvature model when it was subjected to complex forces/torques, such as gravity, grasping forces and driving torques. In this case, the Cosserat theory was used to implement real-time computations of the grasping force of the soft robotic gripper that was subjected to complex forces. Finally, a series of tests were conducted on the grasping force of the soft finger and the gripper. The elicited results showed that the grasping force is related to the stiffness and to the object's offset and friction coefficient. Moreover, experimental results showed that the grasping force of the soft robotic gripper increased by 48.7% when the Young's modulus of the SMA-2 wires increased from 25 GPa to 48 GPa.

1. Introduction

Conventional manipulators and end-effectors, which involve rigid components, such as linkages, gears, and motors, can exhibit precise positioning and improved mechanical performance using the control strategies and algorithms developed during the past decades [1]. However, these types of rigid robots are unsafe and exhibit poor adaptability when they interact with humans or the surrounding environment. In comparison to conventional manipulators, soft manipulators inspired by biology, such as the octopus arms and the elephant trunk, exhibit compliant and safe characteristics [2]. They can perform a variety of tasks, such as dexterous manipulation in limited space or unknown environments. Because the design principles and operation methodologies for soft robots are extremely different from conventional rigid manipulators, many different design mechanisms, fabrication and control strategies have been developed in recent years for these robots [3], including the design of soft actuators [4], fabrication of soft hands [5], and position control of soft fingers [6].

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There is a growing trend towards the development of soft robots to serve human beings and to work with people. A soft robotic gripper is an import part of a soft robotic system that interacts with the environment and objects [7]. In some cases, the soft hands with low stiffness can effectively absorb shocks during interaction with the environment and maintain either adaptive interactions with complex shapes or safe interactions with objects that require protection, such as eggs and fruit [8]. In other cases, soft grippers with increased stiffness can pick up heavy objects, such as water cup and bottle. These advantages have attracted the attention of numerous researchers and steered efforts towards the development of soft hands with variable stiffness [9].

Common methods for grippers with tunable or variable stiffness include the hydraulic pressure, pneumatic particle jamming [10], and layer jamming [11]. However, the use of either additional pump stations, or power equipment, increases the complexity and weight of the robot system, resulting in difficulties for compact and high power-density required in autonomous mobile robots. Moreover, these variable stiffness mechanisms are coupled with the actuating process of soft robot. In addition to these methods, various decoupling strategies for obtaining both actuator and variable stiffness characteristics of soft grippers have been reported, including SMA that has actuator properties and fusible alloy (Ni-Cr wires) with tunable stiffness [12], motor that has actuator properties and magnetorheological fluids with varying stiffness characteristics [13], and a pneumatic actuator and shape memory polymer (SMP) with variable stiffness properties [14]. However, the use of these materials in variable stiffness mechanisms as low-melting alloy, fluids and low-strength polymer make these designed grippers perform the light manipulation tasks.

SMAs falls into the category of smart materials and can execute direct electrothermal actuation with increased strengths. Additionally, SMA actuators possess various advantages, such as low driving voltages, biocompatibility, small size, and noiseless operations, which make them suitable for a variety of applications [15], such as soft robotics [16], robotic surgical systems [17], and grippers [18]. Among the SMA materials, the NiTi alloy has been extensively used for the design of actuators owing to its increased strain characteristics (up to 7%) [19]. Moreover, SMAs can be used to change the stiffness of structures [20]. Nevertheless, the SMA used to induce variable stiffness is not capable of producing large deformations, which are required in soft robots. To overcome these drawbacks, a new soft finger with variable stiffness was proposed [21], but its application design and grasping model remains to be investigated.

In regard to kinematic and static modeling of soft robots, various methods have been developed, such as the improved Denavit-Hartenberg (D-H) approach [22], constant [23], and variable curvature [24] methods. These approximate methodologies are valid for soft robots in the absence of external loading [25]. However, the interaction of soft fingers with various objects is sensitive to not only gravity but also bending torques and varying loads. The Cosserat theory has been recently used to model kinematics and dynamics of continuum robots, and it has shown promise as a general tool used to describe the finite deformations of soft robots that withstand complex forces and torques [26]. However, the Cosserat theory was generally used in continuum robots [27] and was rarely applied to multi-finger soft hands with complex loading.

The main contribution of this study is the introduction of the design and implementation of a grasping model of a new soft robotic gripper with variable stiffness. Its uniqueness lies in the structural decoupling of the actuator and the variable stiffness mechanisms of the soft robotic gripper. The actuator mechanism is realized by one thermal-induced SMA fiber with contraction in length, and the variable stiffness mechanism is realized by another thermal-induced SMA wire without change in length. In addition, a stress-induced SMA fiber with super elasticity is used as the bone structure to provide the initial stiffness and restoring force of the soft fingers. Owing to the complexity of the developed forces or torques, such as gravity, grasping force, and bending torque, the kinematics and statics of the soft robotic gripper cannot be analyzed using the conventional constant-curvature model. Based on the Cosserat theory, a grasping force model is built for the proposed soft robotic gripper with variable stiffness. Moreover, a series of experimental tests and simulations on the grasping force of the soft robotic gripper are investigated to discuss the modeling properties.

The rest of this paper is organized as follows. In Section 2, a soft robot gripper is developed. A Cosserat theory-based model of the grasping force is introduced in Section 3. In Sections 4 and 5, the experimental results are compared with the simulation results for the soft finger and gripper. Finally, conclusions and comments on future work are outlined.

2. Soft robotic gripper with variable stiffness

To investigate the grasping force of soft hands with variable stiffness, we designed a soft robotic gripper, as shown in Fig. 1. This soft gripper includes two fingers that are fixed using one foundation bed, where both fingers are completely identical in size and structure. The detailed configuration and partial enlargement of the soft finger are shown in Fig. 2. The SMA-3 wire (0.6 mm in diameter, NiTi alloy) with super elasticity is used as the bone structure to ensure that the soft finger can restore after bending [28], whereas four SMA-2 wires (0.5 mm in diameter, NiTi alloy) without change in length are fixed in parallel to the SMA-3 wire to realize the variable stiffness of the soft finger. The effective lengths of the fingers are referred to as the working lengths of the SMA-3 and SMA-2 wires, denoted as $L_3 = L_2 = 100$ mm. To actuate the soft finger, one SMA-1 fiber (0.15 mm in diameter, BMF150 from Toki Corporation in Japan [6]), which is used 1200 mm in length for large contraction because its strain is low, is placed into both fingers with a U shape to redouble its driving capacity, as well as to conveniently charge at one end of the fingers.

As shown in Fig. 2(a), all SMA fibers were embedded in brackets to stabilize the bending deflection of the fingers and avoid kinking. These brackets were made of polylactic acid (PLA)—the same material used in the foundation bed—using a