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Feasibility Study of a Gripper with Thermally Controlled Stiffness of Compliant Jaws

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Abstract: This paper proposes a simple and compact compliant gripper, whose gripping stiffness can be thermally controlled to accommodate the actuation inaccuracy to avoid or reduce the risk of breaking objects. The principle of reducing jaw stiffness is that thermal change can cause an initial internal compressive force along each compliant beam. A prototype is fabricated with physical testing to verify the feasibility. It has been shown that when a voltage is applied, the gripping stiffness effectively reduces to accommodate more inaccuracy of actuation, which allows delicate or small-scale objects to be gripped.

Keywords: compliant mechanisms; gripping; stiffness reduction; thermal control

1. Introduction

The ability to handle delicate/fragile or small-scale objects is very useful, but challenging, since such materials are either very sensitive to the gripping force or too small to easily control the tiny actuation. Creating a gripper mechanism that applies exactly the right amount of force to grip such an object without breaking it can be done in several ways: one active approach is to use force sensing technology to accurately control actuation displacement [1,2], and another method is to use preloading displacement to generate a constant force from the jaw mechanism over a relatively large displacement range to accommodate the actuation inaccuracy [3]. The goal of this paper is to design and build a compact handheld compliant gripper that is simple enough to use and is capable of varying gripping force of the same actuation displacement (i.e., varying gripping stiffness) for grasping different objects. Devices like tweezers or tongs would be unsuitable, because they require the hand to coordinate with sensory feedback (sight and touch). In the case of objects that are very small or very brittle, sensory feedback is imperceptible [3].

Therefore, it is constantly required to find a way to regulate the gripping force so that it does not exceed the breaking force of the object. Using the electrothermal properties of materials to actuate micro-grippers in MEMS (micro-electromechanical systems) has been reported in [4–6] for biological manipulations, where the motion of two jaws is actively controlled by the thermal deformation of the functional material (polymer with very high thermal expansion coefficient). Electrothermal control-based shape memory alloy actuators were also proposed for force tracking control of a flexible gripper in [7]. Motivated by those works, the alternative method adopted in this paper also involves the use of material thermal properties for gripper design. However, the proposed method aims to manipulate (reduce) the gripping stiffness of the gripper's jaw (rather than actively controlling the motion of jaws by thermal actuation), which allows the human user to roughly control the gripping force of the system based on the strength property of the objects. In such a way, there is no need to have precise control/sensing of the force applied on the object, but this is enough to avoid (or reduce the risk of) exceeding the breaking force.

The design of such a desired gripper is demonstrated in Figure 1. The compliant gripper is a symmetrical design, where two jaws have rectilinear rigid-body motion towards the opposite direction to grip the object. Each half of this gripper is composed of two major compliant mechanisms: one is the parallel mechanism (actuation is imposed upon it) for guiding the jaw, so that the two jaws can only have parallel motions without producing slipping force on the object [2]; The other part is the jaw mechanism itself, which uses the symmetrical compound parallelogram mechanism [8] to change gripping stiffness. To control the stiffness, a simple heating coil is wrapped around the compliant beams of the jaw mechanism to dissipate heat for the beams. When a voltage is applied across the heating coil, the beam is heated up (without causing motion of the jaws), therefore decreasing the stiffness and allowing delicate or small-scale objects to be gripped.

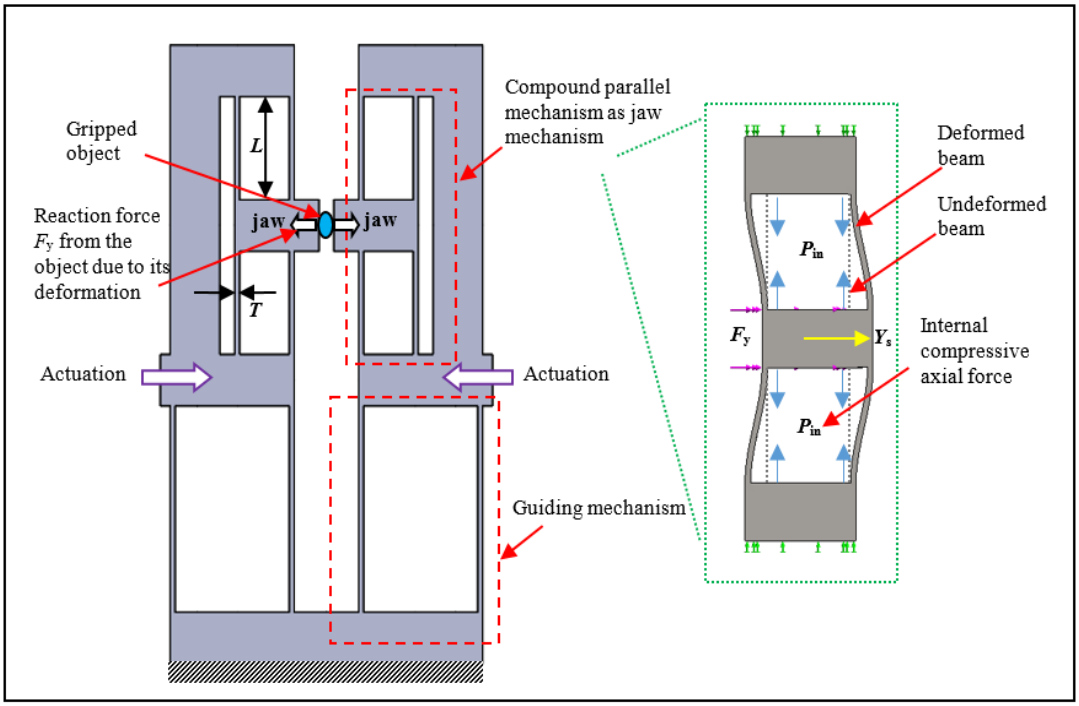


Figure 1. Schematic design of the proposed monolithic symmetrical gripper.

2. Theoretical Basis

The compound parallelogram mechanism (Figure 1) is a well-behaved translational joint with a high compliance in the direction of the degree of freedom (primary motion) and very large stiffnesses in the directions of the degree of constraints. It is also a symmetrical design without undesired parasitic motions inherently accompanying the primary motion. The primary motion of the compound parallelogram mechanism (i.e., the jaw's gripping motion) is controlled by the equation below [8]:

$$y_s = \frac{f_y}{48 + 2.4\left(\frac{1.2y_s^2 + 2p_{in}/d}{1/d + y_s^2/700}\right)} \quad (1)$$

In Equation (1), all symbols are dimensionless and represented by corresponding lower-case symbols as defined in [8], which means that all geometrical parameters are divided by the length (L) of identical beams; forces by $E(UT^3/12)/L^2$. T and U are the beams' in-plane and out-of-plane thicknesses, respectively; E is the Young's modulus of the beam material. The symbol y_s is the relative motion between the actuation displacement and the jaw's actual displacement, which is equal to the deformation displacement of the object; The symbol f_y is the reaction force from the object when gripping occurs, which is equal to the gripping force. d is equal to $12/(T/L)^2$. p_{in} is the initial internal

axial force applied on each beam, which should be much larger than −10 in order to avoid first-order buckling, and will be induced by the thermal control in this paper. Here, a positive value of p_{in} represents the tensional axial force, and a negative one stands for the compressive axial force. It can be observed that when the magnitude of the negative p_{in} increases, the force/stiffness at the same displacement (y_s) reduces. The geometrical parameters also affect the stiffness of the jaw, which is not discussed in this paper, but can be seen in [8].

The relation between the initial internal axial force and the thermal change is explained as follows. Considering a slender beam (Figure 1) without any constraints on either of its ends, we can have the following expression to consider the change of beam length that corresponds to a change in temperature [8]:

$$\Delta L = \alpha \int_0^L \Delta T(L) \mathrm{d}L \tag{2}$$

where ΔL is the final length change when the final steady-state temperature change is ΔT (varying along the beam). The symbol α is a simplified constant value; i.e., mean coefficient of thermal expansion.

Due to the fact that both ends of the beam in the compound parallelogram mechanism are fixedly constrained, the length change by temperature increase is actually zero, which in return induces the initial internal compressive axial force. The magnitude of initial internal axial force can be calculated in terms of the temperature change by using the result in Equation (2) as below [8]:

$$\begin{aligned} & p_{\text{in}}/d = \Delta L/L \\ & \Rightarrow p_{\text{in}} = d\alpha \textstyle\int_0^L \Delta T(L) \mathrm{d}L/L \end{aligned} \tag{3}$$

If temperature is uniform along the beam for simplification, Equation (3) reduces to $p_{\text{in}} = d\alpha\Delta T$, suggesting that the internal axial force magnitude is proportional to the temperature increase.

3. Feasibility Study

In this section, a feasibility study is implemented to take into account material selection, manufacturing method, and testing prototype and results. Further discussion follows to clarify the inherent issues of the proposed design and future improvements.

3.1. Prototype Fabrication and Testing

There are three materials for the coil, jaw mechanism, and guiding mechanism, respectively. The heating coil material is selected to be annealed stainless steel wire with 0.635 mm diameter, which is able to produce a high enough temperature change. The jaw mechanism's material is polycarbonate, with a Young's modulus of 2.3 GPa, yield strength larger than 60 MPa, a relatively high coefficient of thermal expansion of 70×10^{-6} K^{-1} for easy thermal control in changing gripping force/stiffness, and which is not conductive. The material for the guiding mechanism and other parts was aluminum alloy 1060, due to its suitability in compliant mechanisms.

The main parts were fabricated by precise CNC (computer numerical control) milling machining, and the coils were wound by hand with 23 turns along each beam in the jaw mechanism. The final prototype is shown in Figure 2 with an overall planar dimension of 9 cm × 15 cm, which is compact enough to be operated by hand. Note that an asymmetrical assembled prototype (with one jaw mechanism) was manufactured for simplicity, although it is not consistent with the original symmetrical and monolithic one (with two jaw mechanisms, as proposed in Figure 1). However, this does not affect the verification of the feasibility study in this paper. The beam length (L) and in-plane thickness (T) of the jaw mechanisms are 20 mm and 1 mm, respectively, with the out-of-plane thickness U = 5 mm. There was 3 mm of space between the two gripping surfaces in the original non-deformed configuration. The gripper prototype consisted of five separately fabricated components: the jaw mechanism (polycarbonate), the frame with guiding mechanism (aluminum alloy), top plate (aluminum alloy), bottom plate (aluminum alloy), and heating coil (annealed stainless steel). The jaw

mechanism was arranged in the middle of the top and bottom plates, in the same plane as the frame with guiding mechanism. Bolts were used for assembly, and electrical tape was used to insulate the coil from the conductive plates.

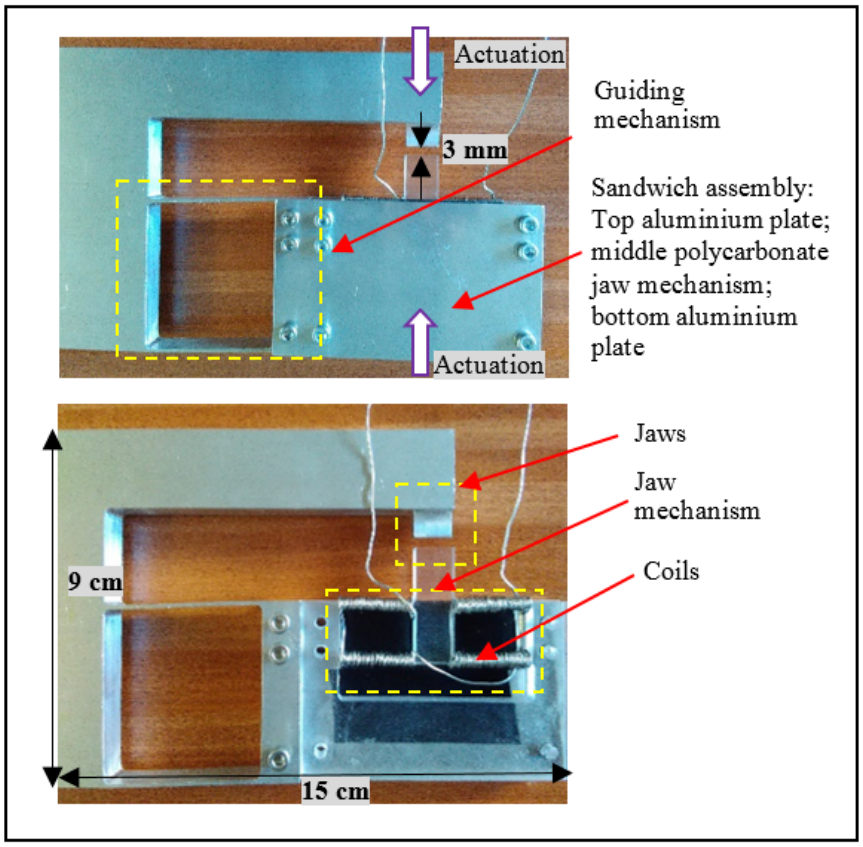


Figure 2. Fully assembled asymmetrical gripper shown next to a hand for reference (**above**); top plate removed, revealing the heating coil (**below**).

Changing the jaw stiffness is done by simply turning on the heating coil circuit that is powered by an 8 V battery, and then waiting for some time until steady status. For verification of the main principle of the device, it must be shown that the application of heat is actually able to effectively reduce the stiffness of the jaw mechanism. The jaw mechanism with and without heat was tested in a single-axis by a single-axis TA.HD Plus Texture Analyzer. A set of displacements were applied in the jaw mechanism, and the corresponding reaction forces were recorded.

Figure 3 shows the comparisons of two (average) testing results with and without heat for the case study. It has been proven that the heat can effectively reduce the gripper force/stiffness of the jaw mechanism based on current/voltage control, as expected. If the breaking force of the intended object is 10 N, the maximal acceptable displacement of the jaw is about 0.65 mm without heat control, and is close to 1 mm with heat control. Therefore, the heat control can better compensate for the actuation inaccuracy. If a lower gripping stiffness/force is required, a higher voltage should be applied, as long as the beam does not have buckling. Additionally, a hysteresis loop between loading and unloading testing has been observed for the polycarbonate material, where the heat can amplify the hysteresis phenomenon.

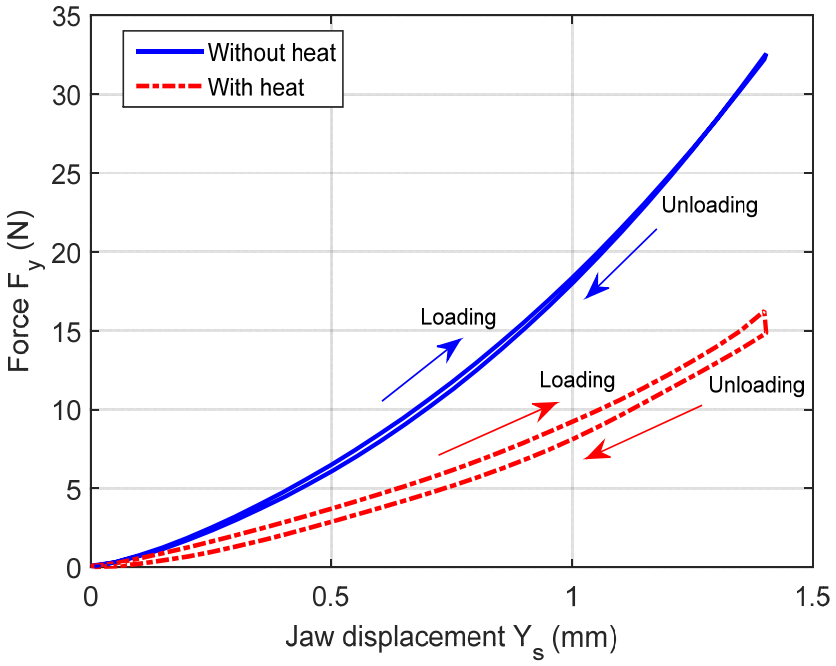


Figure 3. Testing results of the jaw mechanism with and without heat.

3.2. Further Discussions

Although the feasibility of designing a gripper with thermally controlled stiffness of compliant jaws has been validated, there are some issues, exposed below. Firstly, the heating coil may be not an optimal heat dissipating method, with low-repeatability of coil windings and temperature control. In the future, an improved heating method for the beams should be investigated. A possible approach is to evaporate the thin-layer of electrically-conducting material on beams, which dissipates heat to heat up the beams by voltage control. Secondly, the relation between the applied voltage and the desired thermal change remains unclear. An accurate voltage control circuit in terms of accurate temperature change (corresponding to a change of internal compressive axial force) is to be investigated. Thirdly, the proposed design can only reduce the risk of breaking materials (accommodating actuation inaccuracy) by changing the stiffness of the jaw mechanism, while exactly knowing/controlling the gripping forces on the level of mN, etc. is impossible in current design. In order to address the third issue, we can bond a sensitive pressure sensor on the gripping surface to sense the small gripping force.

It should be noted that, compared to electrothermally-activated grippers [4–7], thermal control in this paper cannot result in any motion of two jaws due to the symmetry of the jaw mechanism; additionally, the jaws always have parallel motion, regardless of the presence or absence of imposing heat, which can eliminate the slippery force on the object.

4. Conclusions

A compliant gripper has been presented in this paper which has the ability to vary the stiffness of the jaw in order to grip delicate/fragile materials and handle small-scale objects to tolerate actuation inaccuracy. The proposed design is also simple, compact, and low cost. An asymmetrical prototype has been fabricated and tested. The testing results show that the thermal control can effectively reduce the gripping stiffness.

The proposed design can not only be used as a hand-held device, but can also be embedded into a robotic gripper (by adding a mechanism actuating the two guiding mechanisms simultaneously [2]) for various practical applications.

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Author Contributions: Guangbo Hao proposed the design idea and wrote this paper. Mehdi Riza fabricated the prototype and implemented the testing.

Conflicts of Interest: The authors declare no conflict of interest.

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