ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 16 (2016) 708–716

Available online at www.sciencedirect.com

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Original Research Article

Design and static testing of a compact distributed-compliance gripper based on flexure motion

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ARTICLE INFO

Article history:
Received 17 February 2016
Accepted 23 April 2016
Available online

Keywords:
Gripper
Compliant mechanisms
Distributed-compliance
Compactness
Testing

ABSTRACT

There are precision issues with traditional rigid-body grippers due to their nature in presence of joints' backlash and friction. This paper presents a macroscale compliant gripper to eliminate these issues for the applications in handing delicate/brittle materials such as powder granular or manipulating sub-millimetre objects such as optical fibre and micro-lens. The compliant gripper is obtained from a 2-PRRP (P: prismatic; R: revolute) kinematic mechanism, and uses distributed-compliance joints for avoiding stress-concentration and enabling large range of motion. A very compact design is achieved by using a position space principle. The compliant gripper is modelled, fabricated, followed by comprehensive testing for characterising relationships between the input displacement/force and output displacement and between the input displacement and displacement amplification ratio, and for analysing hysteresis during loading and unloading. The experimental results are compared with finite element analysis (FEA) model and linear analytical model. The testing results have suggested good performance characteristics of this compliant gripper such as a nearly linear relationship between the input and output, a nearly constant amplification ratio for closing the jaw, and negligible hysteresis error.

1. Introduction

Traditional rigid-body grippers often suffer from issues of poor resolution and repeatability associated with backlash and friction inherent in their joints [1], which are thus not suitable for handing delicate/brittle materials such as powder granular or manipulating sub-millimetre objects such as optical fibre and micro-lens. Compliant mechanisms (CMs), aka flexure mechanisms, transfer and transform motion, load and energy by deformation of their flexible members (materials) [2–4], which are good candidates to remove the above mentioned issues in traditional grippers. In addition, CMs can be easily miniaturised, can reduce the number of parts (thereby raising the system reliability) and are free of assembly by a monolithic fabrication. CM-based grippers (compliant gripper) have been successfully used in the applications of precision robotic manipulation, biomedical devices and microelectromechanical systems (MEMS) [5–15].

There are mainly two methods to design a compliant gripper: structure optimisation method [12,14,15], and kinematics-based substitution method [5–10,13]. The former design approach is to re-consider the design task as an optimal material distribution problem so that the resulting

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http://dx.doi.org/10.1016/j.acme.2016.04.011
1644-9665/

structure can fulfil the specified motion requirements. The optimisation approach based design involves three aspects: (a) topology, i.e. the connectivity of material, (b) size, i.e. the cross-sectional area of each segment, and (c) geometry, i.e. the orientations of the connecting segments and locations of the junctions [12]. For example, Zhu et al. [15] conducted topology optimisation of hinge-free compliant mechanisms with multiple outputs using a level set method. However, this optimisation approach generates compliant mechanisms that can be highly sensitive to manufacture error. The latter design approach is the one that we intend to use in this paper due to the well-known simplicity and clear kinematic meaning. The general procedure to use this approach to design a gripper can be shown as follows:

(a) Selecting a proper rigid-body kinematic mechanism with/without an input amplification mechanism;
(b) Choosing proper compliant joints to replace traditional joints in the rigid-body kinematic mechanism;
(c) Arranging relative positions of adjacent compliant joints if possible for most compact design;
(d) Check if the final compliant gripper meets the design requirements. If not, repeat the above steps.

Using the kinematics-based substitution method, lumped-compliance joints (or flexure hinges) [5–10] are often chosen since they enable to directly replace their rigid-body counterparts in the traditional parallelogram mechanisms, slider-crank mechanisms, and straight-line linkages [5–10], in order to design a compliant gripper. For example, Ref. [10] reported an asymmetric flexible micro-gripper mechanism based on flexure hinges, where the parallelogram mechanism is employed to guide motion of one jaw with the input displacement amplified by a lever mechanism. However, lumped-compliance leads to limited motion range, and can cause stress-concentration issues and especially requires a large actuation force. The large actuation force is able to be offered by piezoelectric (PZT) actuators with high-precision [5–10]. The use of a PZT actuator requires pre-stressing and particularly needs a displacement amplification mechanism [5–10,16] to amplify the input displacement since the PZT actuator only produces tiny displacements. Despite the merit, the introduction of a displacement amplification mechanism adversely degrades the resolution of the actuator. Due to the hysteresis issue from the PZT actuator [17], an open-loop control is not feasible. Moreover, it is still a challenging open issue to design a very compact compliant gripper since the compliant gripper's configuration is usually limited by its rigid-body kinematic mechanism when using the lumped-compliance joints.

Based on the above advances, there is a necessity in this paper to design a new and simple macroscale compliant gripper based on the following *desired design specifications*, which enables more selections of compliant grippers in different application requirements.

- *Linear output in horizontal direction only for each jaw*: This requires an output linear guiding mechanism to connect with each jaw so that sliding motion between the gripped object and the jaw can be maximally avoided, and also an even distribution of the gripping force over the manipulated sample can be achieved.
- *One linear input only*: This is required due to the fact that most high-precision linear actuators such as voice coil (VC) actuator are linear ones and cannot tolerate transverse displacements/loads. This demands an input linear guiding mechanism to control jaws simultaneously. Usually, it is desired to have the whole gripper with smaller size in the horizontal direction and therefore the linear actuator is better to be arranged in the vertical direction.
- *Large range of motion*: This desired characteristic refers to the large motion of the jaw to accommodate the large diameter change of grasped objects, which requires the use of distributed-compliance joints/modules when designing a gripper. Distributed compliance can avoid stress-concentration as well as large actuation force. The use of distributed-compliance joints enables the use of high-precision actuators with low force but large displacement output such as a VC actuator to be selected in this paper without needing an amplification mechanism (no resolution degrading). The large range of motion requires a symmetric design to enable both jaws to move as opposed to an asymmetric design in [10]. It is noted that the use of a VC actuator also requires a symmetric design for alleviating thermal sensitivity.
- *Compactness of mechanisms*: This means that the resulting gripper should have a large ratio of motion range to the mechanism's overall dimension. It is therefore desired to consider the embedded arrangements for adjacent compliant joints. If compliant revolute joints are to be selected, these with remote rotation centres should be given priority since they may reduce the mechanism footprint significantly.

The remainder of this paper is organised as follows. Section 2 elaborates the design of a compact large-range compliant gripper followed by a linear analytical kinetostatic modelling. Fabrication, testing and result comparison and analysis are provided in Section 3. Finally, conclusions are drawn.

2. Design of a compact large-range gripper

Based on the first two design specifications mentioned above, a simple 1-DOF (degree of freedom) 2-PRRP (P: prismatic, and R: revolute) kinematic mechanism (Fig. 1) is a good solution to be used as the traditional kinematic mechanism for designing a compliant gripper. Each PRRP mechanism is a double slider mechanism [18] and it can act as a displacement amplification or reduction mechanism without assistance of other mechanisms. This PRRP mechanism is a more general representation of other motion amplification or reduction mechanisms such as the bridge-type flexure mechanism [16]. The kinematic principle and all geometrical parameters are indicated in Fig. 1. Here, θ_{R1} and θ_{R2} are the rotational angle of the two R joints, and δ_{P1} and δ_{P2} is the translational displacement of the two P joints. $\delta_{in} = \delta_{P1}$ is the input motion from the linear actuator, and $\delta_{out} = \delta_{P2}$ is the motion of each jaw, which is the output of the gripper.

In order to achieve a large range of motion, two distributed-compliance joints [2] (Fig. 2) are selected to replace the traditional P and R joints in Fig. 1 where each compliant P joint is a basic parallelogram mechanism and each compliant R joint is an isosceles trapezoidal flexure mechanism with a remote rotation centre. The two compliant P joints (or compliant R joints) are identical in the compliant gripper.