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Research paper

Nonlinear analysis and optimal design of a novel piezoelectric-driven compliant microgripper

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ABSTRACT

In a piezoelectric-driven microgripper, obtaining parallel grasping and enlarging grasping stroke are important. This paper presents the nonlinear analysis and optimal design of a novel orthogonal displacement amplification mechanism (DAM)-based piezoelectric-driven microgripper without using traditional bridge-type mechanism or multi-stages DAM, which realizes parallel grasping and displacement amplification simultaneously in compact configuration and benefits further miniaturization. The structural design of proposed microgripper is given, in which a novel orthogonal DAM is used as the intermediate mechanism. The geometrical nonlinearity analysis of novel orthogonal DAM is conducted, including the finite difference-based analysis, the variance-based global sensitivity analysis and the correlation analysis. Based on the nonlinear analysis results, a static constraint restricting the large deflection geometrical nonlinearity degree is established. An optimal design framework of the proposed microgripper is further formulated, which maximizes the grasping movements with considering the property of piezoelectric stack actuator, the nonlinear geometric constraints, the established static constraints as well as the dynamic constraint. A design example verifies the optimal design framework, which can reduce the negative effect of large deflection nonlinearity on the orthogonal movement transformation without requiring specific experience. Experimental tests are used to verify the parallel grasping and the displacement amplification of microgripper.

1. Introduction

Recently, microgrippers become important end-effectors in micro-manipulation, such as micro-particle handling [1,2], optical fibers assembly [3,4] and cell manipulation [5,6], in which parallel grasping is preferred for stable manipulation. With the advantages of high displacement resolution, fast response and large bandwidth, piezoelectric actuator is widely applied in micro-manipulation. The essential components of a piezoelectric-driven microgripper include the actuator, the intermediate mechanism and the grasping arms. For facilitating manipulation, large grasping movement is inclined to whereas the stroke of piezoelectric actuator is limited, leading to that the intermediate mechanism is generally designed as a dis-

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placement amplification mechanism (DAM). Parallel grasping and DAM have become the key issues of piezoelectric-driven microgrippers.

Being free of clearance, friction and assembly error, compliant mechanisms are widely used to construct DAM, such as leverage mechanism [7], bridge-type mechanism [8], Scott-Russell mechanism [9], and topology optimized DAM [10]. Compared with other DAMs, bridge-type mechanism can realize orthogonal movement transformation. A typical case is that for obtaining parallel grasping, the movement of jaws should be perpendicular to the input force generated by the actuator [11–13], which can be realized by bridge-type mechanism. The static model, optimization [14], dynamic test [15] and improvement [16,17] of bridge-type mechanism have been presented. In order to eliminate the parasitic movements at the output ports, fully symmetric configuration and bidirectional symmetric input forces/displacements are required in bridge-type mechanism. Whereas for typical piezoelectric stack actuator (PSA), it is more convenient and stable for preload when fixed at one end, in which the symmetric bidirectional movements are transformed into the unidirectional movement [18,19]. Moreover, the miniaturization of bridge-type mechanism is affected by the preload and installation of PSA. Some multi-stages DAM can realize orthogonal displacement amplification as well [20,21], which significantly increases the size of microgripper. Both bridge-type mechanism and multi-stages DAM are widely used in the already existing microgrippers. A novel single-stage orthogonal DAM without requiring bidirectional symmetric input forces/displacements is proposed in our previous research [22], in which the preload of PSA is independent of the DAM design. Undetermined elastic bodies are introduced and the corresponding design equations have been derived. Furthermore, the static and dynamic models are established. Potentially, the proposed orthogonal DAM can be used for the actuators with typical unidirectional movement, such as the PSA with one fixed end [18], lateral comb electrostatic actuator [11], arrays of electrostatic actuators [23], and chevron electrothermal actuator [24].

However, in an orthogonal DAM, the input force is perpendicular to the amplified output displacement. Therefore, the moment is not only influenced by the structural parameters but also influenced by the deflection, leading to large deflection geometrical nonlinearity. For large deflection modeling, several approaches are available, including elliptic integral solution [25], finite difference method [26], chain algorithm [27] and pseudo-rigid-body method [28]. For a nonlinear index, the sensitivity analysis is important. As a straightforward sensitivity analysis method, increment-based method [29,30] can only measure the sensitivity at a specific point. Partial derivative can be used to conduct sensitivity analysis [31], whereas complex nonlinear response is hard to be dealt with by partial derivative. Both increment-based method and partial derivative cannot obtain the sensitivity of interaction among the parameters. For a nonlinear index, variance-based global sensitivity analysis [32] can determine the most sensitive design variable across the whole input space. In our previous research on the novel orthogonal DAM [22], the derived design equations, static models and dynamic models are based on small deflection assumption, whereas the nonlinearity analysis has not been conducted. Besides, the design framework before has difficulties on determining the preset parameters as it may require specific experience. In the field of compliant mechanism, optimal methodology can be applied to find the suitable parameters automatically [13,33].

In this paper, the nonlinear analysis and optimal design of a novel compliant orthogonal DAM-based piezoelectric-driven microgripper will be presented. The structural design of proposed microgripper will be given in Section 2. The geometrical nonlinearity analysis of novel orthogonal DAM will be conducted in Section 3. Based on the nonlinear analysis results, a static constraint restricting the large deflection geometrical nonlinearity degree can be established. In Section 4, the optimal design framework of proposed microgripper will be formulated with considering the property of PSA, the nonlinear geometrical constraint, the established static constraint as well as the dynamic constraint. In Section 5, a design example will be given and the optimal design result will be verified by finite element analysis (FEA). In Section 6, the microgripper prototype will be fabricated and experimental tests will be used to verify the displacement amplification and the parallel grasping of microgripper.

2. Structural design of a novel piezoelectric-driven compliant microgripper

In this section, a piezoelectric-driven microgripper utilizing the novel orthogonal DAM will be designed.

The proposed orthogonal DAM is a triangulation amplification-based mechanism (as shown in Fig. 1a). Sliding pair I is designed as symmetric structure and sliding pair IV is replaced by an undetermined elastic body, in which three undetermined parameters are needed [22]. Fig. 1b schematically illustrates the proposed DAM, which is a statically indeterminate mechanism with uniform thickness h. The stiffness of flexures beside the input structure is much smaller than that of the input structure. Different from bridge-type mechanism, the requirement for bidirectional symmetric input forces/displacements is avoided and the typical unidirectional input force/displacement is used. The type of flexure hinges is arbitrary. For improving the deformation ability, leaf-type flexure hinges can be used. The in-plane dimensions of flexure-based beam AB are determined by the smallest width of flexure hinges t and the theoretical displacement amplification ratio Q_t. The undetermined elastic body can be designed as a constant cross-section beam with three undetermined parameters, as shown in Fig. 1c. The undetermined parameters are chosen as L_d, B, γ. Further, the design equations of undetermined beam CD are derived by the linear elastic assumption-based compliance matrix method, the displacement boundary conditions as well as the load equilibrium equations [22]:

$$\Gamma_{XC-FZC}\eta + \Gamma_{XC-FXC} + \Gamma_{XC-MC} f_1 \eta + \Gamma_{XC-MC} f_2 = -q\,, \quad (1)$$