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A new topology optimization method for planar compliant parallel mechanisms

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ABSTRACT

This paper presents a new method for the optimal synthesis of planar compliant parallel mechanisms (CPMs). The compliant limbs of CPMs are regarded as separate design domains of topology optimization problem. The finite element analysis (FEA) and matrix methods are combined to analyze the CPMs' Jacobian and stiffness matrices, based on which a new formulation is proposed for the topology optimization of multiple degree-of-freedom (DOF) compliant mechanisms. Without beginning with a known rigid-body mechanism, the proposed method finds the optimal topology of CPMs within the given design domains. The ability of the proposed method to find the optimal topology with complex kinematic behavior is demonstrated by several numerical examples and experimental study.

1. Introduction

The CPMs can provide the merits of both parallel and compliant mechanisms. These merits include high stiffness, high load carrying capacity, and high precision. The potential applications of CPMs are the situations that require micro-precision or ultra-precision manipulations.

The advantages of compliant mechanisms compared with their rigid-body counterparts have raised a growing interest in developing the methods for their conceptual synthesis. Two main synthesis approaches in this challenging area are the rigid-body replacement approach [1–3] and topology optimization approach [4–7].

The CPMs are usually synthesized by the rigid-body replacement approach. This approach seldom creates new topologies for CPMs according to design problems, but begins with the existing topologies from rigid-body mechanisms and replaces their kinematic joints with flexural hinges. So majority of the CPMs proposed in the literature share the same topologies with their rigid-body counterparts. For example, the 6-DOF CPMs designed by Hudgens et al. [8,9] and the 3-DOF planar CPMs proposed by Yi et al. [10–12]. To a great extent, the CPMs are the ramifications of rigid-body parallel mechanisms in the field of compliant mechanisms. The conceptual synthesis of CPMs depends on the type synthesis methods [13–16] of rigid-body parallel mechanisms. This dependence may induce the following two problems.

(i) The synthesis methods of rigid-body parallel mechanisms focus on enumerating all possible topologies, and are unable to solve the problem of topology selection currently. So designers cannot use the best rigid-body mechanism topology to design CPMs for particular tasks.

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(ii) The kinematic topologies obtained by the rigid-body synthesis methods may not be suitable for compliant mechanisms. After all, force and displacement in compliant mechanisms are inseparable and must be considered simultaneously [17], which is more complicated than that of rigid-body mechanisms.

As two methods without this dependence, the freedom and constraint topology (FACT) approach proposed by Hopkins and Culpepper [18] and the screw theory based method proposed by Yu et al. [19] are new contributions to the type synthesis of CPMs. However, performance of topology is still not taken into account by these two methods. Consequently, a systematic synthesis method considering the topology performance is needed by the CPMs.

On the other hand, the problem of topology selection is solved very well by the topology optimization approach from a structural viewpoint. This approach can achieve the optimal topology, shape, and dimension of a single-piece compliant mechanism from the design specifications directly, without beginning with a known rigid-body mechanism [20,21]. In other words, this approach combines the two steps in the conceptual design of mechanisms, i.e., type synthesis and dimensional synthesis, into one step to select the best configuration for a specific design problem. Due to this advantage, extensive efforts have been conducted on the topology optimization approach which includes the ground structure method [20,22], homogenization method [23–26], and level set method [27–30].

However, the mechanisms designed by this approach are almost limited to the planar compliant mechanisms with single input and output ports, e.g., inverter and gripper. Here, the term "output port" is regarded as a prespecified point in the design region where the displacement along a prescribed direction is desired [31]. Only a few researches applied topology optimization techniques to the compliant mechanisms with multiple input or output ports. For example, Frecker et al. [5] extended topology optimization to the compliant mechanisms with multiple output ports using a multi-criteria formulation. Sigmund [32,33] designed the multi-physics and multi-material actuators with multiple input and output ports using topology optimization. Saxena [31] studied the topology optimization of large displacement compliant mechanisms with multiple materials and multiple output ports. Lu and Kota [34,35] studied the topology optimization with non-fixed ports and proposed the load path representation, in which the input, output, and grounded ports can take different coordinates. Topology optimization was also extended to the synthesis of 3D compliant mechanisms [36–38], but focused on the case of single input and output ports. On the whole, the multi-criteria topology optimization discussed above is to control the displacements of multiple output ports under the excitation of single input or multiple inputs. The controlled output displacements are almost limited to the two translational freedoms in x- and y-axes, and rotational freedom is seldom considered.

The synthesis of CPMs cares more about the DOF of the output point at platform, rather than specific displacements of multiple output ports. The DOF of platform can be up to three and six for 2D and 3D CPMs, respectively. It is not easy to use specific displacements to describe the multi-DOF motion any more, especially in 3D cases. Thus, the topology optimization of CPMs is more complicated than that of the compliant mechanisms with multiple input and output ports. The multi-criteria topology optimization methods cannot be applied to the synthesis of CPMs directly. One alternative way is to introduce the basic idea of topology optimization into the area of CPMs synthesis. Following this new idea, our previous works [39–41] have made some attempts in the optimal synthesis of flexure-based compliant mechanisms. Reference [39] synthesized the multi-DOF passive compliant mechanisms by optimizing the compliance characteristics of mobile platform. References [40,41] proposed a new synthesis method for 1-DOF pseudo-rigid-body mechanisms based on the idea of topology optimization. Heading in the similar direction, Lum et al. [42,43] recently presented a hybrid topological and structural optimization method to design a 3-DOF CPMs. This method firstly synthesizes the compliant joints with the optimal stiffness characteristics by topology optimization. The optimal compliant joints are then assembled together to form a CPM using the topology of existing rigid-body mechanisms.

This paper intends to develop a new synthesis method considering the topology performance for planar CPMs from a structural viewpoint. This method is a new extension of the topology optimization techniques, but employs a different formulation based on the Jacobian and stiffness matrices to evaluate the overall performances of multi-DOF CPMs. Unlike the traditional CPMs, the CPMs obtained by the proposed method possess the structural topology, which will be a new addition to the topology of CPMs.

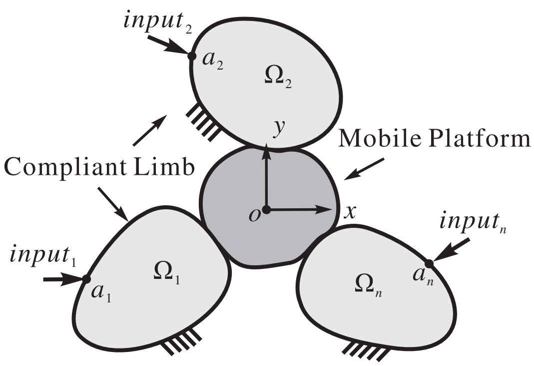

Fig. 1. General design domain of planar CPMs.