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Original Research Article

Designing a monolithic tip-tilt-piston flexure manipulator

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ABSTRACT

This paper deals with the design of a monolithic tip-tilt-piston flexure manipulator for high-precision applications. The manipulator is first proposed with consideration of actuation isolation, which is a symmetrical and compact design and can be monolithically fabricated without using additive manufacturing. Kinematic and kinetostatic models are then analytically derived for quick parameter assessments. A case study is discussed finally, where a monolithic prototype has been made using CNC milling machining, comparisons among analytical, FEA and testing results are also undertaken.

1. Introduction

Tip-tilt-piston parallel mechanisms are constantly required in the applications of wrists/solar panels/thrusters [1], articulated tool heads [2], manipulators [3,4], and machining robots [5]. This kind of parallel mechanism can provide three in-plane (XOY plane) DOC to allow three out-of-plane DOF including one translation along the Z-axis, and two rotations along the X- and Y-axes, respectively. Here, DOF and DOC denote degree(s) of freedom and degree(s) of constraint, respectively. Based on the type of the kinematic joints used, we can classify the tip-tilt-piston mechanism into two sub-types including traditional rigid-body mechanism composed of only traditional kinematic joints, and flexure mechanism composed of only compliant/flexure joints. In high-precision applications such as micro mirrors and nano-positioning systems [6,7], traditional mechanisms are not suitable due to their inherent issues such as backlash, friction, wear, and lubrication. However, flexure mechanisms [8] that employ deformation of flexible members to transfer motion, force or energy should be good candidates for such applications if there is only requiring small range of motion in millimetre scale. This paper intends to propose a new tip-tilt-piston flexure manipulator with simple kinematics that can be monolithically fabricated and easily controlled [7].

Flexure mechanisms can be free of assembly, due to their ability to be monolithically manufactured using well-developed machining methods such as water jet, milling machining and wire electrical discharge machining [9]. Nevertheless, the monolithic fabrication is mostly true for the flexure mechanisms with planar motions [9,10]. For demanding one or more of out-of-plane (spatial) motions as specified in this paper, it is hardly to have monolithic fabrication due to the complication of spatial design, although Ref. [11] reported a successful XYZ decoupled flexure manipulator that has been monolithically

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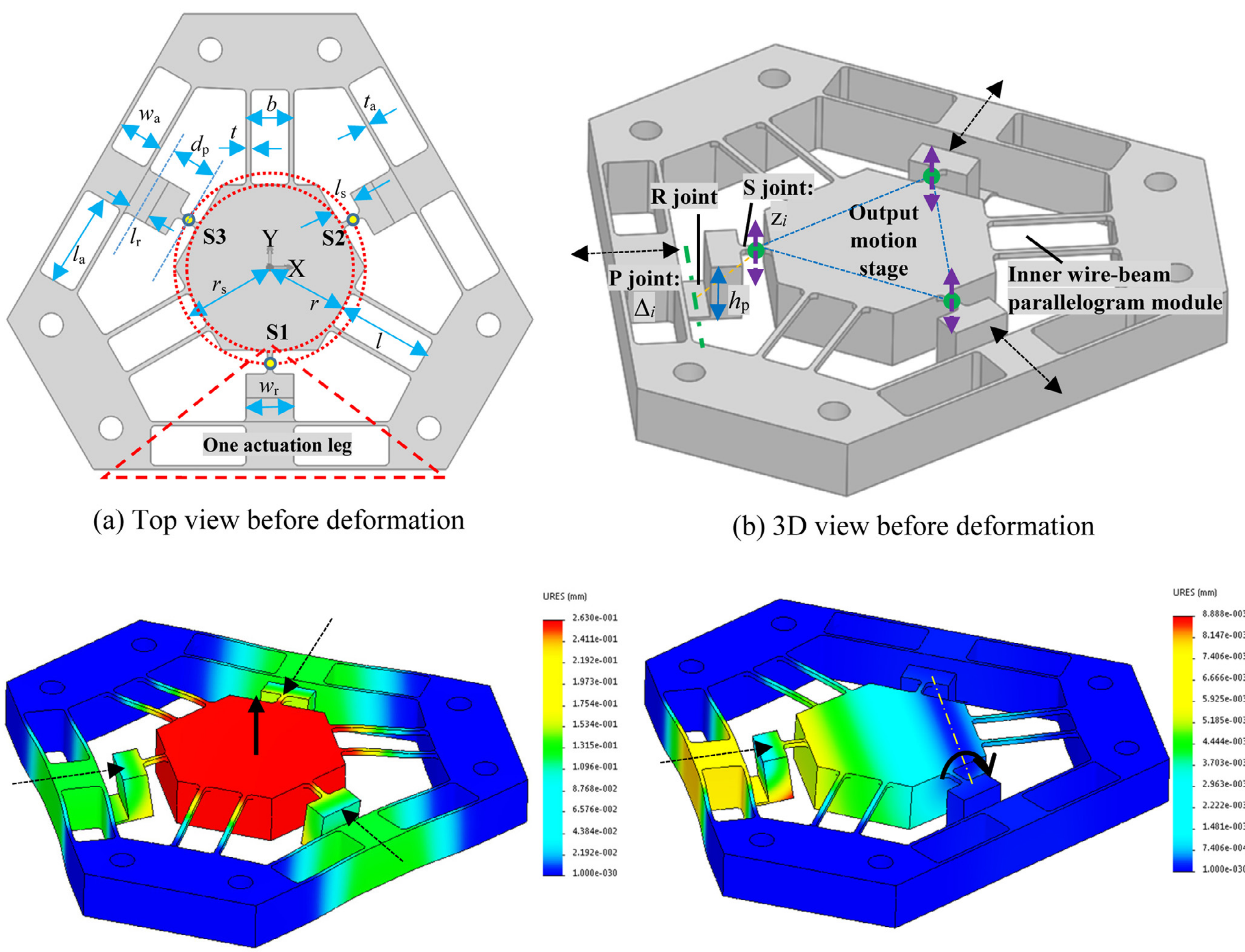
manufactured. Therefore, assembly has to be used for most emerging designs with out-of-plane motion requirements [12,13], despite assembly leads to serious issues such as assembly error, increased number of parts, reduced stiffness by bolted joints, and increased cost. Over recent two decades, additive manufacturing (3-D printing) technologies have grown fast where complex parts made from one or more of base materials (e.g. engineering plastics, ceramics and metal) can be printed. However, there is no traditional heat treatment and exists material anisotropic issue associated with layer-by-layer printing process, which make the 3-D printed parts are not feasible for flexure mechanisms. In addition, the advances of design methods in flexure mechanisms can form foundation for the work of this paper. For example, the constraint-based design [14], FACT [15], and other screw-theory-based design methods [16] can be applied to design flexure mechanisms with different mobility requirements. However, those existing approaches mainly serve to design compliant modules without considering actuation isolation (i.e. passive mechanisms) [17,18]. Our solution is to design a symmetrical passive mechanism with desired mobility at first, using the existing methods [14–16] such as constraint-based design. Three appropriate actuation legs are then designed and symmetrically added on the output motion stage to implement active control (with actuation isolation), with an appropriate arrangement for enabling monolithic fabrication.

This paper is organised as follows: Section 2 presents the structure of the tip-tilt-piston flexure manipulator. The following Section 3 implements kinematic and kinetostatic modelling analytically. A case study is comprehensively discussed in Section 4 where a monolithic prototype has been physically made and tested. Section 5 concludes this paper finally.

2. Design of a monolithic tip-tilt-piston flexure manipulator

A monolithic tip-tilt-piston flexure manipulator with actuation isolation is proposed in Fig. 1, which is a fully symmetrical design. Its desired mobility (three out-of-plane DOF) is determined by the firstly-designed passive mechanism, consisting of three wire-beam parallelogram modules



(a) Top view before deformation

(b) 3D view before deformation

(c) Three equal actuation forces resulting in translation along the Z-axis only, using FEA

(d) One actuation force resulting in coupling rotation and translation for the centre, using FEA

Fig. 1 – The monolithic mechanism with three isotropic actuation legs.