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Design, fabrication and testing of a novel symmetrical 3-DOF large-stroke parallel micro/nano-positioning stage

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ABSTRACT

Limited travel stroke constrains the application of existing XYZ parallel micro/nano-positioning stages. In this paper, a novel parallel-kinematic symmetrical micro/nano-positioning stage is proposed to enlarge the travel range with a compact physical size. For a large-stroke parallel stage, the cross-axis motion increases the difficulty of closed-loop control process. The motions of the parallel stage on different axes are decoupled by employing I-shaped flexure hinges in this work. In order to obtain a large input displacement for actuating the stage, three voice coil motors (VCM) are adopted. In view of the lower output force of the VCM, the guiding flexure mechanism is designed with an optimized cross-sectional dimension. To verify the performance of the stage, analytical modeling and simulation study are carried out. A prototype stage is fabricated for experimental studies. Results show that the designed parallel micro/nano-positioning stage owns a three-degree-of-freedom motion workspace of 2.22 mm × 2.22 mm × 1.81 mm with an overall size of 176 mm × 176 mm × 198 mm, which is more compact than existing symmetrical designs containing the actuators. Moreover, the symmetrical design enables a low crosstalk of 1.7% among the three working axes.

1. Introduction

In modern precision engineering field, micro/nano-positioning stages have been widely applied in various situations, such as atomic force microscopy [1], micromanipulation of biological cells [2], microassembly of robots [3], and so on. In order to get rid of friction, backlash and lubrication in traditional joints (such as revolute and prismatic pairs), flexure hinges are usually employed. As a compliant mechanism, flexure hinge delivers the motion by resorting to the elastic deformation of the material [4,5]. It not only overcomes the aforementioned disadvantages of traditional joints [6], but also obtains some advantages such as low cost. Thus, flexure mechanisms are widely applied in recent micro/nano-positioning stage design.

Regarding kinematic scheme, flexure micro/nano-positioning stages fall into two categories in terms of serial and parallel kinematics [7]. A combination of both schemes constructs a hybrid kinematics [8,9]. Generally, a multi-degree-of-freedom (DOF) serial-kinematic stage is composed of several 1-DOF modules which are successively connected in serial. Although it is possible to yield a compact design, cumulative errors and non-equal dynamics property in different axes are the major disadvantages. By contrast, parallel-kinematic stage overcomes such issues and enables a high stiffness and high loading capability for the stage system [10–13]. Thus, parallel-kinematic flexure stages have attracted enthusiastic interests of recent works [14–17]. However, in comparison with serial-kinematic mechanism, parallel-kinematic one possesses a relatively small motion range. Especially, due to the relatively small rotation angle of elastic flexure hinges, parallel-kinematic flexure stages typically can only offer a motion range less than 1 mm in each working axis [18]. In practice, many applications require the positioning ranges over 1 mm in each axis to realize a dexterous operation, such as robotic micromanipulation of zebrafish embryos [19].

The motion range is vital for the wide application of parallel micro/nano-positioning stage [20]. To broaden the application of parallel positioning stage, much work has been devoted to enlarge the motion range. For example, the motion range of a micro/nano-positioning stage is enlarged as millimeter level so as to adopt a novel sample-holder device in an atomic force microscope [21]. To develop a metrological atomic force microscope and to obtain the performance in the measurement of lateral dimension, a large-range dual-stage scanning device is employed in [22]. In order to realize a large stroke in parallel-kinematic mechanism, the greatest challenge lies in how to decouple the cross-axis motion, especially for multi-DOF mechanism. In the literature, by using a pair of orthogonally located right-circular flexure hinges, three monolithic limbs obtain both input and output decoupling properties for the XYZ nanopositioning stage proposed in [23]. Besides, a geometrical decoupling process is reported in [24] by applying leaf flexure hinges

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Table 1
Comparison of the performance of typical XYZ stages.

Stage	Travel range (mm^3)	Stage size (mm^3)	Compactness	Symmetrical
[27]	1.0×1.0× 1.0	–	–	No
[24]	10×10×10	–	–	No
[18]	0.13×0.13×0.13	110×110×110	1.7×10^{-9}	No
[28]	3×3×3	350×350×350	6.30×10^{-7}	Yes
[15]	1.5×1.5×1.5	105×105×105	2.9×10^{-6}	No
[29]	10×10×10	466.4×466.4×466.4	9.85×10^{-6}	No
This work	2.2×2.2×1.8	176×176×198	1.45×10^{-6}	Yes

located in parallel, which obtains 1.5% isolation rate of the entire motion range.

Intuitively, a large motion stroke can be generated by using a relatively large physical size of the flexure mechanism. However, a large physical dimension is not allowed in some applications, such as micromanipulation inside a scanning electron microscope [25]. Therefore, it is desirable to realize a large stroke while maintaining a compact size of the stage [26]. Moreover, in order to suppress the parasitic rotation and crosstalk translation of the output platform, it is desirable to design a totally symmetrical XYZ stage. In this work, the compactness index of the mechanism is defined as the ratio between the product of travel ranges along the three working directions over the volume of the stage physical size. The larger the compactness ratio, the more compact the structure, which indicates a wider application in limited space and lower cost in terms of material and fabrication.

The main contribution of this work is the design of a new symmetrical XYZ parallel-kinematic flexure stage with large stroke and compact design. The symmetrical design is implemented to reduce the parasitic rotational motions and the crosstalk among the three translational motions. For illustration, the compactness ratio of typical XYZ stages are tabulated in Table 1. Although the XYZ stage as reported in [29] is more compact than the presented one, its structure is not symmetrical and the actuators need to be added for drive. Such issues are not reflected in the compactness ratio. The XYZ stage presented in this work owns a totally symmetrical structure, which enables the reduction of the parasitic rotational motions and the crosstalk among the three translational motions. That is, it leads to a pure translational motion in the three working axes without unwanted motions in theory. Compared with the totally symmetrical XYZ stage as studied in [28], the proposed stage has improved the compactness ratio by 2.3 times.

Moreover, in comparison with the existing XYZ stages of other forms are shown in the literature [30,31], the proposed one in this work offers a larger pure translational output platform, which can be used to carry big devices such as micro-injector for micro-surgery applications. The remaining parts of the paper are organized as follows. The mechanical design is described in details in Section 2. Analytical model is derived in Section 3. The stage performance is evaluated by performing finite-element analysis (FEA) simulation in Section 4. Prototype fabrication and experimental study are presented in Section 5. Section 6 gives the conclusion.

2. Mechanical design of the 3-DOF flexure parallel stage

In this section, the mechanism design of the 3-DOF parallel micro/nano-positioning stage is introduced.

2.1. Design and assembly process

A CAD model of the designed XYZ parallel flexure stage is shown in Fig. 1. The cube-like stage is driven by three linear actuators, i.e., voice coil motors (VCMs) in this work. The central part is fixed and the outer frame functions as the output platform of the stage. Such design provides a large platform for mounting different end-effectors towards different applications. Instead, by fixing the outer frame and using the inner part

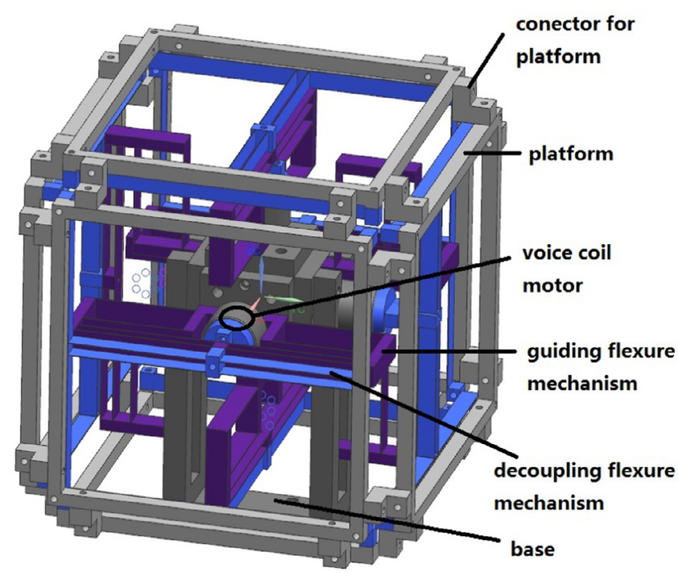

Fig. 1. CAD model for the designed XYZ parallel flexure stage.

as the output platform, an alternative design can be obtained. Basically, the presented stage owns a structure of 3-PPP (P stands for prismatic joint) parallel mechanism. Each P joint is realized by a combination of multiple leaf flexures.

The VCM can offer a large travel. The guiding flexure modular not only ensures the pure translational movement of the VCM, but also improves the location accuracy of VCM. In addition, the decoupling flexure modular can obtain isolated motions. To facilitate the fabrication of the decoupled large-stroke 3-DOF flexure mechanism with high productivity efficiency, the concept of modular design is adopted. The assembly process of the entire stage is illustrated in Fig. 2. In the first step, the fixing modular is assembled by a base and two support pillars as shown in Fig. 2(a). The base with four positioning holes can be connected to the isolated platform by fastening bolt. The flexure guiding mechanism is connected to the fixing modular by connector 1 in Fig. 2(b) as step 2. The symmetric location of flexure guiding mechanism (FGM) can dismiss the moment of force to prevent the rotation motion. In step 3, the VCMs (model: NCC04-10-005-1A, from H2W Techniques, Inc.) are adopted to drive the FGM as shown in Fig. 2(c), which is applied to guide the large stroke motion. Considering the large mass of VCM-A, it is assembled to the fixing end. So, the coil part of VCM-B is connected to the flexure guiding mechanism by connector 2. In step 4, the I-shape flexure mechanism (ISFM) is applied owing to its fine decoupling property. Finally, the six platforms are assembled as one part by connector 3 in step 5 and step 6. In this way, the platform is actually connected to the base by FGM and obtains decoupling motion by ISFM.

For a compliant mechanism using leaf beams, there is a significant reduction on the stiffness in constraint direction over the primary motion. Due to the fine decoupling property, the wire beam is useful in stage design with actuators placed outside [32]. But in the case of output platform which owns a big mass itself caused by the inside located actuators, the leaf flexure is more suitable. And the fabrication accuracy of the wire beams is hard to control in terms of mean dimension. Therefore, leaf flexures are adopted in this work.

The 3D integrated fabrication method is a fast and popular way in many research such as [32]. While in this paper, the actuators need to be assembled inside to obtain a compact structure with a large output platform. Thus, the modular design is adopted. As a result, the 3D fabrication is replaced by 2D fabrication which is more convenient in practice. Unavoidably, the assembly process will introduce assembly error and stiffness loss due to the bolting connection.