A 3-DOF Spatial Motion Flexure-Based Parallel Manipulator with Large Workspace and High Payload for UV Nanoimprint Lithography Application

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Abstract

This paper presents a 3-DOF (θx-θy-Z) Flexure-based Parallel Manipulator (FPM) that serves as an UV Nanoimprint Lithography (UV-NIL) tool head to meet the stringent process requirements, i.e., nanometric linear resolution, sub-arc-second angular resolution for co-planarity alignment, high payload, and direct-force control capability throughout a large workspace of a few millimeters and degrees.

1 Introduction

A FPM is a closed-loop compliant mechanism whereby the moving platform is connected to the base through parallel legs, which are formed by a series of flexure joints [1]. Benefiting from the advantages of the elastic-deflection of the flexure joints and the closed-loop architecture of the parallel kinematics, the FPM bears the essential features of a nanopositioner such as frictionless and wear-free motion, absence of mechanical play, insensitive to thermal variations, and high dynamic stability etc. Hence, such FPMs have been widely used in high-precision manipulation applications because the flexure joints offer a cheaper and maintenance-free solution as compared to other non-contact bearings, e.g., the air-bearings or the magnetic-bearings etc. With the aid of electromagnetic actuations, recent efforts have also shown that some FPMs could achieve large workspace of several millimeters [2]. However, the low payload characteristic of these FPMs becomes unfavorable for the UV-NIL imprinting processes.

2 3-legged Prismatic-Prismatic-Spherical FPM

To realize the desired θx-θy-Z motion, a novel 3-legged Prismatic-Prismatic-Spherical (3PPS) parallel kinematic configuration is introduced (Figure 1).

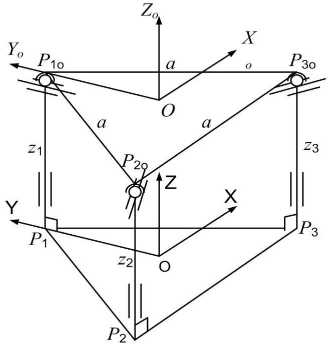

Figure 1: Schematic diagram of 3PPS

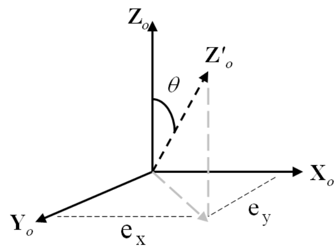

Figure 2: Vector projection of orientation

2.1 Kinematic Analyses

Kinematic analyses show that the proposed 3PPS parallel configuration can only orientate about the planar X-Y plane and thus offers a single solution in both forward and inverse kinematic analyses. The forward kinematic solutions are given as follows

$$e_x = \frac{z_2 - z_3}{a} \quad e_y = \frac{2z_1 - z_2 - z_3}{a\sqrt{3}} \quad z = \frac{1}{3}\left(z_1 + z_2 + z_3\right) \qquad \text{Eq.1}$$

In addition, the inverse kinematic solution are given as follows

$$z_1 = \frac{a\ e_y}{\sqrt{3}} + z \quad z_2 = \frac{3a\ e_x + \sqrt{3}a\ e_y}{6} + z \quad z_3 = -\frac{\sqrt{3}a\ e_x - a\ e_y - 2\sqrt{3}z}{2\sqrt{3}} \qquad \text{Eq.2}$$

As a result, the derived solutions in both forward and inverse kinematics allow a simple yet efficient joint-space or task-space control scheme to be implemented.

2.2 Beam-based Flexure Modules

The proposed 3PPS parallel configuration is subsequently articulated as a FPM by replacing the joints with three proposed flexure joint modules as shown in Figure 3. These modules include the active prismatic flexure modules, the passive prismatic flexure modules, and the passive spherical flexure modules. Each flexure module employs the beam-based flexure joints coupled with rigid-links of various lengths to achieve larger deflection (Figure 4).

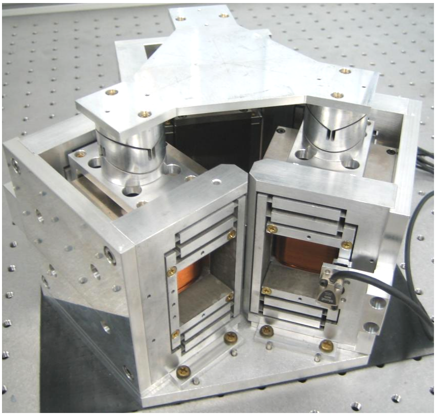

Figure 3: Prototype of 3PPS FPM

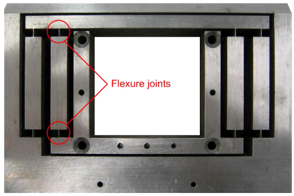

Figure 4: Prismatic flexure module

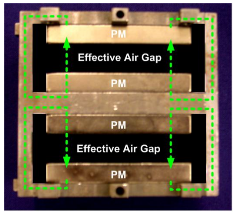

Figure 5: DM configuration

2.3 Electromagnetic Actuation Modules

Electromagnetic actuators are used to achieve large displacement. Here, the magnetic circuit of each electromagnetic actuator adopts a Dual-Magnet (DM) configuration (Figure 5) to enhance the magnetic flux density within the effective air-gap, which consequently increases the output force [3].

3 Experimental Investigations

A LEICA laser tracker is used to evaluate the achievable displacement of the developed 3PPS FPM and shown that the FPM is capable of achieving a large workspace of 5° x 5° x 5mm. A laser interferometer and an autocollimator are also used to evaluate the positioning and orientation resolution of the FPM respectively. Through a joint-space control scheme, the measurements taken from the effector of the prototype show that the FPM has achieved an open-loop positioning resolution of ±10 nm and an orientation resolution of ±0.05 acrsec. Figure 6 plots the 20 nm positioning steps performed by the FPM. Lastly, Figure 7 shows that the FPM has high-payload capability with at least 15-Kg loading limit.

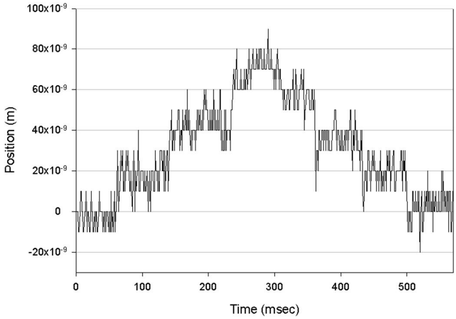

Figure 6 : 20 nm positioning steps

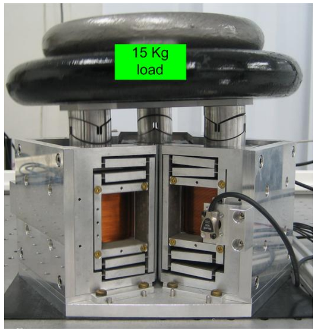

Figure 7: High payload capability

4 Summary

A 3-DOF 3PPS FPM has been developed and achieves a position and orientation resolution of ±10 nm and 0.05″ respectively, and continuous output force of 200N throughout a workspace of 5° x 5° x 5mm. In this work, a 3PPS parallel architecture is proposed. Kinematic analyses have shown that the proposed configuration offers a single solution in both forward and inverse kinematic analyses. In addition, this configuration allows the linear actuator to be mounted vertically on the base, which directly translates the force generated from the actuator to the end-effector. Thus, the developed FPM provides capabilities such as direct-force control, active co-planar nano-alignment, and high loading capacity etc, which meet the stringent process requirements of an UV-NIL process.

References:

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[2] X. Tang, I-Ming Chen and Q. Li, "Design and nonlinear modeling of a large displacement XYZ flexure parallel mechanism with decoupled kinematic structure", *Review of Scientific Instruments*, vol. 77, pp. 115101-11, 2006.

[3] T. J. Teo, I.-M. Chen, G. L. Yang, and W. Lin, "Magnetic field modeling of a dual-magnet configuration", *Journal of Applied Physics*, vol. 102, pp. 074924-12, 2007.