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Design and quasi-static characteristics study on a planar piezoelectric nanopositioner with ultralow parasitic rotation

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A B S T R A C T

This paper presents a particular mechanism design which is inherently inclined to have no parasitic rotation. The flexure-based stage comprises symmetric flexure guiding mechanism and two piezoelectric stack actuators. The layout of the stage is evaluated by finite element analysis, and the results indicate that the proposed design exhibits ultralow parasitic rotation. A prototype of the stage is then fabricated, and its performance is tested. Experimental results show that the stage has a stroke of 500 μm × 500 μm and the crosstalk is less than 1%. The maximum parasitic rotation is ±1.2 arcsec at a stroke of 500 μm.

1. Introduction

Nanopositioners are commonly used in microscopy, micromanufacturing, and microcontrol systems. A two-degree-of-freedom (DOF) planar nanopositioner indicates that the stage has only two translational motions, which are along the *X* and *Y* directions. Theoretically, the stage has no rotational motion around the *Z*-axis. In practice, however, parasitic rotations always occur on a flexure planar stage; this is because of manufacturing defects or simplification in analytical modeling. The parasitic rotation must be kept as low as possible. This is because the nanopositioner usually has a very limited working area and produces a small map with details when the nanopositioner is applied in microscopy. The total field of view can be expanded by stitching small maps together and create a big map with details as well. The low parasitic rotation is a critical factor to guarantee the stitching quality. Large area micromanufacturing also requires perfect stitching without misalignment. This study proposes an approach for achieving this demand.

In [1], a positioner with a serial mechanism was proposed, and this positioner had a parasitic rotation of 0.75 arcsec at a stroke of 100 μm. In a serial mechanism, two 1-DOF linear stages are joined in a stacking manner. The lower stage carries the upper stage. A serial mechanism has lower parasitic rotation compared with a parallel mechanism because the *X* and *Y* motions of parallel designs are inherently coupled. However, the lower stage of a serial positioner must actuate more mass than parallel stages do, markedly degrading the dynamic performance of the system.

Some techniques are used to reduce the coupling effect on parallel stages, and such techniques include adding an additional 2-DOF guiding mechanism for each axis [2–5] or using leaf-type flexure mechanisms instead of notch-type hinges to connect the mounting part and the moving part [6–12]. Parasitic rotations have been reported only in [2,3], and these rotations are 4.68 and 5.4 arcsec. Other studies have mostly discussed crosstalk; however, parasitic rotation is a more challenging issue. Crosstalk is the unwanted “linear motion” of *Y*-axis when the stage is commanded to go along *X*-axis. If this unwanted amount is detectable, the controller can give new outputs to two actuators to compensate this crosstalk error as low as possible. However, parasitic rotation is the unwanted “angular motion”. The controller cannot compensate this error unless the positioner has a redundant actuator to generate independent yaw motion. And of course, an extra sensor to detect yaw motion is also needed. Equipping more sensors and actuators leads to higher cost. The motivation of this paper is to solve this problem without adding any sensor or actuators. Our method is to design a mechanism with naturally ultralow yaw motion when the stage moves in the *XY*-plane. The details are described in the next section. Simulations and experiments are followed to validate the proposed design.

2. System design

According to a kinematic analysis of screw theory [13], we determine that the mechanism shown in Fig. 1 has two DOFs. Obviously, the two DOFs are linear motions along the *X* and *Y* directions, meaning that the stage does not have the DOF of θ_z (rotational motion around the *Z*-axis). This property is the

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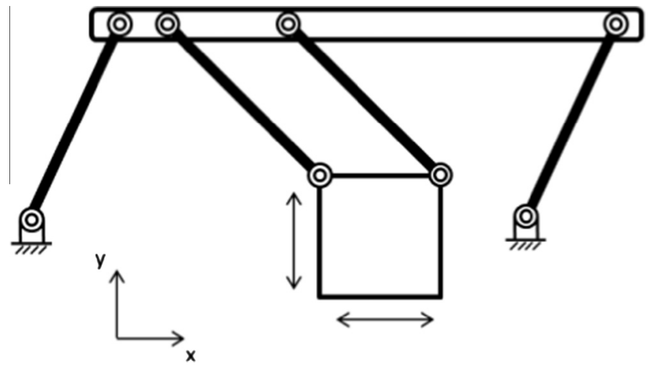

Fig. 1. Stacked parallelogram four-bar mechanism has two DOFs. The orientation of the moving stage is always the same during translational motion.

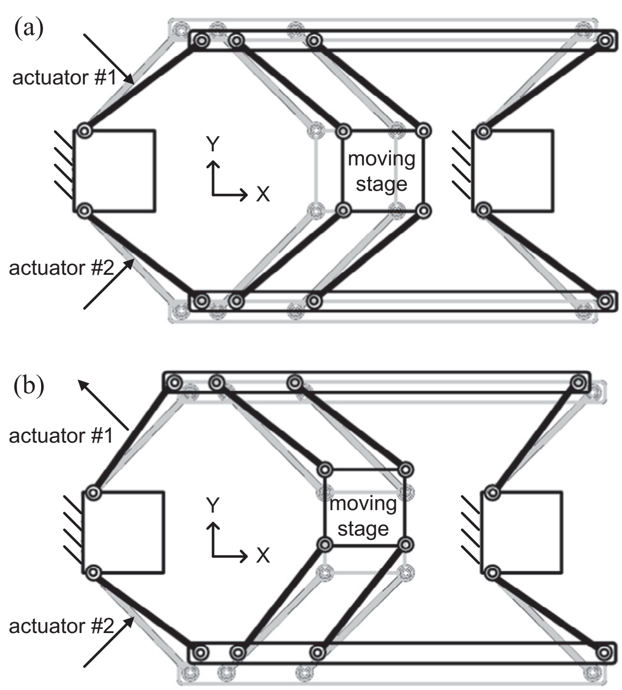

Fig. 2. (a) In-phase and (b) out-of-phase actuation cause motion along *X*-axis and *Y*-axis, respectively.

fundamental concept of the mechanism of the proposed stage. Therefore, the stage is inherently inclined to have a low parasitic rotation.

The proposed stage is designed with the objective of moving it in the *X* and *Y* directions with the same travel ranges. Therefore, we design a stage with symmetric guiding mechanism and a 45° layout of limbs as illustrated in Fig. 2. In Fig. 2(a), when both actuators push the mechanism (in-phase motion), the stage moves along the *X* direction. In Fig. 2(b), when actuator #1 pulls and actuator #2 pushes (out-of-phase motion), the stage moves along the *Y* direction. In this manner, the moving stage can be driven to everywhere on the *XY* plane within its workspace.

For precision purpose, the proposed stage equips piezoelectric stack actuators (PSA), which produce pushing force rather than pulling force. Referring to Fig. 3(a), initially both PSAs extend 0% and the stage rests at the left limit position, which is set as the origin. When both PSAs extend 50%, the stage moves rightward to (250 μm, 0), where is the center of the workspace. When both PSAs fully extend, right limit position (500 μm, 0) can be arrived. If two PSAs extend unequally, motion along *Y*-axis can be contributed. When PSA #1 is off and PSA #2 extends fully, the stage moves to upper limit point. When the actuating condition is reversed, lower limit point can be arrived. The workspace locates on the right half plane. For symmetry, we will define the new origin rightward for half stroke as illustrated in Fig. 3(b). That implies two PSAs have extended 50% during initialization. Now the workspace distributes in four quadrants symmetrically.

To analyze the workspace more specifically, the kernel portion of Fig. 2 is drawn as a skeleton presentation in Fig. 4. We obtain

$$\vec{S_1} = L_2 e^{\frac{i\pi}{4}} + L_3 + L_2 e^{\frac{-i\pi}{4}}, \tag{1}$$

$$\vec{S_2} = L_2 e^{i\left(\frac{\pi}{4}-\theta_1\right)} + L_3 + L_2 e^{i\left(\frac{-\pi}{4}+\theta_2\right)}, \tag{2}$$

and the displacement vector of the moving stage, $\vec{S}$, is the difference between $\vec{S_1}$ and $\vec{S_2}$. We have

$$\vec{S} = \vec{S_2} - \vec{S_1} = L_2\left(e^{i\left(\frac{\pi}{4}-\theta_1\right)} + e^{i\left(\frac{-\pi}{4}+\theta_2\right)} - \sqrt{2}\right), \tag{3}$$

where L_2 is the length of all guiding limbs and L_3 is the distance between two revolute joints, as dimensioned in Fig. 4. θ_1 and θ_2 are the rotating angles induced by two actuators. Since they are very small and thus can be expressed as

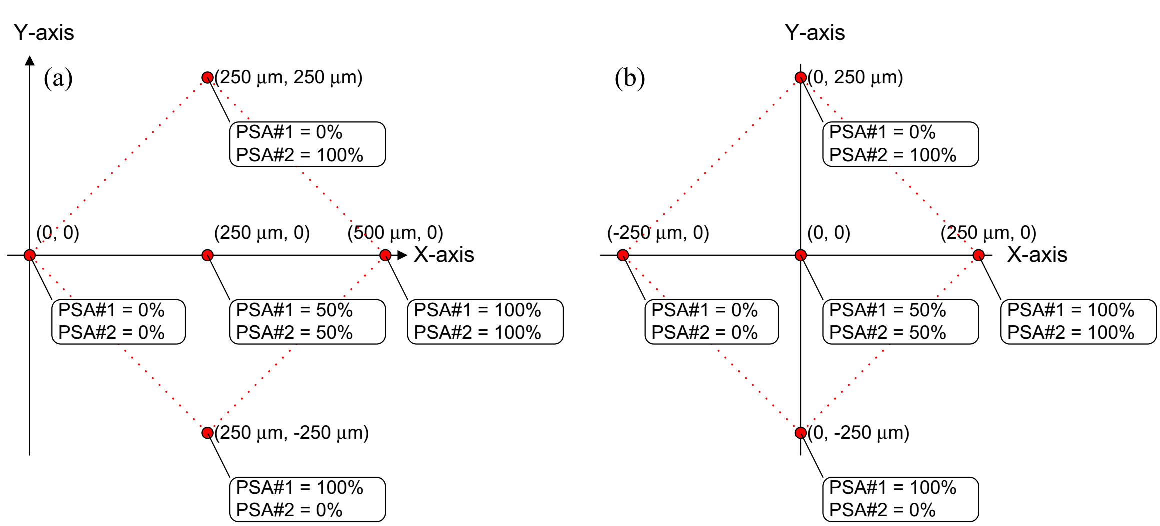

Fig. 3. (a) The original workspace for piezoelectric stack actuators (PSA) that can only produce pushing force. (b) The newly defined workspace with offset origin for symmetry purpose.