



Research paper

Design, optimization and testing of a compact XY parallel nanopositioning stage with stacked structure

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ABSTRACT

This paper presents the design, optimization, fabrication and testing of a new piezo-driven compact XY parallel stage for nanopositioning applications. A decoupled, compact parallel stage is developed by a stacked design, which provides a larger area ratio than existing piezo-driven stages. Displacement amplifiers are adopted to amplify the stroke of piezo-electric actuators. The amplifiers are then improved and integrated with the motion decoupler to isolate the two actuators. The main design variables of the stage are optimized by applying a genetic algorithm based on finite-element analysis (FEA) to achieve the required performance. The optimized design is then further improved to enhance the stage performance, which is verified by performing FEA simulation studies. A prototype stage is fabricated for experimental study. Both open-loop and closed-loop testing are conducted to validate the stage's performance. Results show that the decoupled XY stage possesses a compact dimension of $87.2 \times 87.2 \text{ mm}^2$, which offers a workspace of $212.48 \times 219.24 \text{ }\mu\text{m}^2$ with a resolution of 7 nm.

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1. Introduction

Micro/nano-positioning is an important technique in the field of microelectromechanical systems. Micro/nano-positioning stages are usually employed in precision applications, such as micromanipulation [1–3], microscopy [4–7], and biological cell microinjection [8,9]. Due to the demands of various precision positioning, different kinds of stages have been proposed in the literature. They can be classified into two types in terms of conventional mechanical transmission mechanism and flexure-based compliant mechanism. The first type is based on servomotors, ball screws and rigid linkages. However, it is difficult to provide the ultrahigh precision positioning because of the backlash and friction effects. The second type is based on flexure mechanism. Within the elastic domain, the flexure can provide a precision motion by the elastic deformation of the structure elements. It is extensively used owing to its advantages, such as no backlash and no friction [10–13].

In practice, XY precision positioning stages have been intensively studied owing to their popular applications [14,15]. While extending from single-axis to multi-axis micro/nano-positioning, the main problem lies in how to produce decoupled output motion in different axes. According to the kinematic scheme, there are mainly two kinds of structures, i.e., serial-kinematic structure and parallel-kinematic structure [16]. The output motions of a serial-kinematic XY stage are independent. It is not difficult to obtain a compact size by using the stacked structure. However, it has various problems that

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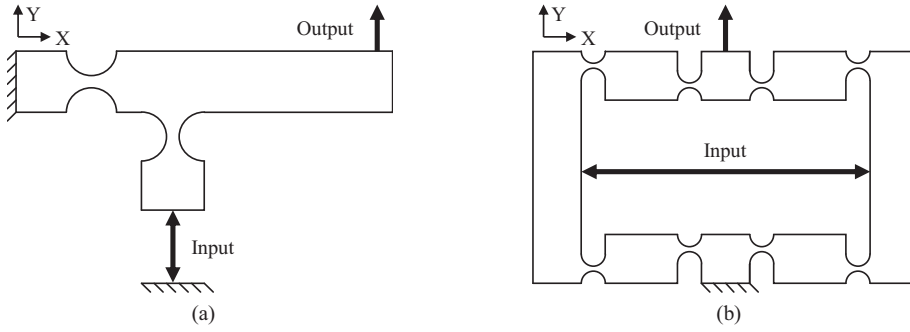


Fig. 1. Illustrations of (a) lever-type amplifier and (b) bridge-type amplifier.

cannot be ignored, such as the high inertia, low stiffness and large cumulative error. Moreover, the dynamic behaviors in different axes are different. Alternatively, the parallel-kinematic structure becomes a more attractive choice to avoid the problems. In previous research, a lots of XY parallel positioning stages have been designed and analyzed by researchers [17–20].

For operating in a limited space, the XY stage is expected to possess a compact structure. Thus, the compactness of the XY stage is an important design criterion. The compactness index can be defined as the ratio between the workspace and device area of the XY stage [14]. A larger compactness index implies that the stage can be fabricated with a smaller footprint size for achieving a defined workspace size. Thus, the larger the index, the more compact the stage structure. Currently, it is still challenging to devise a compact parallel-kinematic XY stage with larger travel stroke driven by piezoelectric actuators. In the literature, parallel-kinematic XY stages with stacked structure have been developed to achieve a compact design [20–23]. However, the existing XY stages exhibit large crosstalk between the two working axes and the structures are not compact enough.

To this end, a new stack-type XY parallel nanopositioning stage is devised to realize a more compact structure with decoupled motion. Analytical modeling, optimization, simulation and experimental studies are conducted to verify the stage performance. The remaining parts of the paper are organized as follows. The mechanism design of the new XY stage is presented in Section 2. The optimization design is performed in Section 3, where the structure improvement and FEA simulation study are carried out. Section 4 introduces the prototype fabrication and open-loop experimental testing results. Section 5 shows the closed-loop testing results and further discussion along with error analysis and comparison study versus existing stages. Section 6 concludes this paper.

2. Mechanical design

In this section, the mechanism design of the XY stage is presented, which includes the stroke amplifier, motion decoupler, and assembly scheme.

2.1. Stroke amplifier design

The stroke of a piezoelectric actuator (PZT) is relatively small. In order to obtain a large enough stroke, a displacement amplifier should be used for amplifying the PZT stroke. According to the working principle, the popular displacement amplifiers can be classified into lever-type and bridge-type mechanisms, as shown in Fig. 1.

The working principle of lever-type amplifier is straightforward. Also, it has a good linearity between the input and output displacements. However, the disadvantage of lever-type amplifier is that its output trajectory is not a pure straight line. To obtain a large amplification ratio, the lever should be long enough or multi-stage level should be used. Both approaches increase the footprint size of the amplifier. Comparing with the lever-type amplifier, bridge-type amplifier can offer a larger amplification ratio with a similar size. This means that a more compact structure can be obtained by adopting the bridge-type amplifier. Moreover, it can provide a pure straight output displacement with a straight input displacement. Therefore, the bridge-type displacement amplifier is used in this work.

The analytical model of a bridge-type amplifier has been derived by elastic analysis in the previous work [24]. The amplification ratio and input stiffness of the whole amplifier can be expressed by (1) and (2) below.

$$A = \frac{\Delta y}{\Delta x} = \frac{K_t l_a^2 \cos^3 \alpha \sin \alpha}{2K_r + K_t l_a^2 \cos^2 \alpha \sin^2 \alpha} \quad (1)$$

$$K_{in} = \frac{2F_x}{\Delta x} = \frac{4K_t K_r \cos^2 \alpha}{2K_r + K_t l_a^2 \cos^2 \alpha \sin^2 \alpha} \quad (2)$$

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