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Review

# A novel 5DOF thin coplanar nanometer-scale stage

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**Abstract**

To minimize the size of a stage with more DOF motion, this paper concentrates on the design, manufacturing process and control of a 5DOF thin coplanar nanometer-scale stage with high accuracy and multiple DOF motion. This paper uses the features of a flexible structure to develop a 200 mm × 200 mm × 35 mm thin coplanar nanometer-scale stage with 5DOF that allows the increase or decrease of axis action in accordance with various needs. The flexible structure of the thin coplanar nanometer-scale stage includes a cylindrical flexible body and an arc flexible body. The thin coplanar nanometer-scale stage allows for three-translational and two-rotational motions and is provided with eight piezoelectric actuators—one on the *X*-axis, another on the *Y*-axis, and the others on the *Z*-axis. The displacement characteristics of the output member of the stage were measured with the built-in capacitive sensors. It also used an analysis and identification controller design method for piezoelectric actuated systems. From the results, it can be seen that the performance of this controller is good and 10 nm controlling error of the step input can be obtained. The controlling error of the rotational angle is about 0.004 arcsec.


*Keywords:* Stack-type stage; Flexure hinge; Nanometer stage; Piezoelectric; Positioning control

## Contents



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## 1. Introduction

In recent years, as the result of rapid developments in various fields of precision engineering, there has been a big increase in the need for precision positioning and scanning systems capable of nanometer or, sometimes, even sub-nanometer resolution and repeatability. This trend is expected to grow, requiring new design concepts and techniques for exploration of more novel devices to meet the demands of various applications. The development of precision machines is important to the study of nanometer-scale manufacturing and research. Ultra-precision stage positioning and nano-measurement technology are two key points in the domain of nanotechnology. For an ultra-precision positioning stage to achieve nanometer accuracy, piezoelectric actuators are commonly used because they have nanometer resolution [1–7]. Recently, the development of a long-range ultra-precision positioning stage has been an important target in the field of nanometer science and technology. Chang et al. [8–12] developed a micropositioning stage with a large travel range. Their stage combines a piezoelectric driving device, flexure pivoted multiple Scott–Russell linkage, and a parallel guiding spring. In 2004, Jywe et al. [13] proposed a new design method of the nanometer positioning stage, which concentrated on the design and manufacturing process of a stack-type nanometer positioning stage with high accuracy and multiple DOF for a heavy-loading machine. No previous work was found on the thinking of the volume of the stage, which might be employed on some applications such as on the application of the stage on an AFM or SPM system. Thus, a thin coplanar nanometer-scale stage could be designed.

In this paper, a flexure hinge-based stack-type 5DOF thin coplanar nanometer-scale stage with high accuracy and multiple DOF is developed. In order to simplify the structure of the stage, the cylindrical flexible body and arc flexible body are the main structures of the designed stage. Actuation of this nano-stage is done with piezoelectric actuators. Capacitive sensors are used for position measurement. The measuring system with multiple capacitance sensors for simultaneously measuring the multi-degrees-of-freedom motion errors is designed and integrated in the stage. Thus, precision positioning feedback can be obtained from the capacitance sensors. Firstly, the structure of this thin coplanar nanometer-scale stage is described. Then, the open-loop system characteristics are experimentally investigated. Based on the results of this investigation, each pair of piezoelectric actuators and corresponding capacitance sensors is treated as an independent system and modeled as a first-order linear model with hysteresis nonlinearity. The method of the analysis and identification for a hysteresis system was used to design a feedforward controller [14], and a PI controller was also designed.

## 2. The structure of the thin coplanar nanometer-scale stage

In this paper, the main purpose of the stage was to provide a micro-translation structure which could improve positioning accuracy and practicality. The thin coplanar nanometer-scale stage designed in this paper is a monolithic structure comprising medium carbon steel. The procedure used uses the features of a flexible structure to develop a thin coplanar nanometer-scale stage. The flexible structure of the thin coplanar nanometer-scale stage included a cylindrical flexible body and an arc flexible body. There are many parts to the flexible structure in the thin coplanar nanometer-scale stage. This flexible structure was assembled by a pre-baking process. It is composed of eight piezoelectric actuators, six adjusted mechanisms, six capacitance sensors, a rigid base, four arc flexure bodies and one four-sided flexure hinge fixture, as shown in Fig. 1. The process used the features of a flexible structure to develop a thin coplanar nanometer-scale stage with 5DOF that allows the increase or decrease of axis action in accordance with various needs. The thin coplanar nanometer-scale stage allows for three-translational and two-rotational motions and is provided with eight piezoelectric actuators—one on the *X*-axis, another on the *Y*-axis, and the others on the *Z*-axis. The displacement characteristics of the output member of the stage were measured with the built-in capacitance sensors. The measuring range of the Physik Instrumente D-015 is 15 μm. A total of six sensors were installed to measure the displacement in the *X*-axis, *Y*-axis and *Z*-axis and rotational motion along the *X*-axis ($\theta_x$) and *Y*-axis ($\theta_y$). The piezoelectric actuators were fastened at each end to the rigid base using the adjusted preload mechanisms. Four piezoelectric actuators (PZT1, PZT3, PZT5 and PZT7) were used to provide the translational motion of the *X*- and *Y*-axis, and another four piezoelectric actuators (PZT2, PZT4, PZT6 and PZT8) were used to provide the translational motion of the *Z*-axis and the rotational motion of the *X*- and *Y*-axis. Piezoelectric actuators are known for the unique features of compact size, swift response, high resolution, electrical mechanical coupling efficiency, and low heat. Therefore, this paper describes the use of piezoelectric actuators instead of conventional actuators.

### 2.1. The working principle of the thin coplanar nanometer-scale stage

The thin coplanar nanometer-scale stage has five-degrees-of-freedom performance by using different parts of piezoelectric actuators (PZT1, PZT2, PZT3, PZT4, PZT5, PZT6, PZT7 and PZT8) to push the flexible body. There are two piezoelectric actuators (PZT1 and PZT5) on the *X*-axis. By using the piezoelectric actuators (PZT1 and PZT5), the stage could be made to move when the PZT1 pushed the four-sided flexure hinge fixture or the other PZT5 pushed the four-sided flexure hinge fixture. There are also two piezoelectric actuators (PZT3 and PZT7) on the *Y*-axis. By using the piezoelectric actuators (PZT3 and PZT7), the stage could be made to move when the PZT3 pushed the four-sided flexure hinge fixture or the other PZT7 pushed the four-sided flexure hinge fixture. There are four piezoelectric actuators (PZT2, PZT4, PZT6 and PZT8) on the *Z*-axis. When the four piezoelectric actuators (PZT2, PZT4, PZT6 and PZT8) pushed the arc flexure bodies, these bodies become and the platform rose. The schematic drawing is shown in Fig. 2. When the two piezoelectric actuators (PZT6 and PZT8) pushed the arc flexure bodies, the platform rose and the rotational angle $\theta_x$