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Development of nanopositioning mechanism with real-time compensation algorithm to improve the positional accuracy of a linear stage

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ABSTRACT

A compensation mechanism with six degrees of freedom (DOF) was developed to enable precise control of a linear stage. Geometric, thermally induced, and dynamic errors in the linear stage were compensated for in real time by the nanopositioning stage. A stage-based hinge with high structural stiffness and rapid response characteristics was modified for parallel operation. The stage's full range of motion was measured and kinematics was used to calculate the displacement required by each actuator to compensate for the errors. Except for the displacement error of the linear stage, the contribution of each error source was measured by a reference mirror and five capacitive sensors. A compensation algorithm, based on a recursive method, was used to improve the positioning accuracy of the system. The performance of the stage presented here was investigated by measuring, and compensating for, the five-DOF linear stage errors in real time. In practice, the peak-to-valley errors of the translational and rotational errors were reduced by 89% and 93%, respectively.

1. Introduction

The performance of linear stages is a key metric in precision industries such as biotechnology, semiconductor technology, and medical optics [1,2]. High-precision linear stages are used in many fields, as demand for accurate positioning has increased in rapidly developing technologies such as electronics and optics [3,4]. Precision linear stages are used to position machine tools and measuring probes accurately in the desired position. Positional accuracy is affected by various factors, which can be broadly classified as geometric, thermally induced, cutting-force-induced, and other error sources [5,6]. A geometric error (typically the most significant type) is the difference between the targeted and final positions of the tool, which can be subclassified as a position-dependent geometric error (PDGE) or a position-independent geometric error (PIGE) [7–9]. PDGEs are caused by component imperfections such as linear displacement, horizontal and vertical alignment errors, and roll, pitch, and yaw rotational errors. These are squareness and offset errors.

Thermally induced errors are caused by the expansion of various stage components due to environmental conditions [10,11]. Heat flow in the system causes nonlinear deformation of the linear guide, ball-screws, and other stage components, resulting in a tool position error. The inaccuracies resulting from these error sources should be eliminated if ultra-precise positioning is to be achieved. The error sources discussed indicate that there are six degree-of-freedom (DOF) errors: three positional errors and three rotational errors. Positional errors are typically measured using offline methods, to improve the accuracy of the stage. The measurement of these error sources has been studied extensively, as they are the most significant [12–15]. Various measurement devices were used to measure the errors associated with the different DOFs of the linear stage. The performance (non-linearity, drift and noise) of the equipment determines the accuracy of the measurement results [16]. Hence, it is necessary to use the optimal sensor for these measurements. Double ball-bars (a simple and convenient measurement tool) have been used to investigate the effects of geometric errors [17,18]. However, it can be difficult to resolve the contribution of each individual error using this method [19,20]. The resolution of ball-bars is also inferior to that of other measurement systems. Laser interferometers yield the most precise measurement of geometric errors [21,22], but only one error can be measured with a single configuration, so the measurement of all geometric errors is

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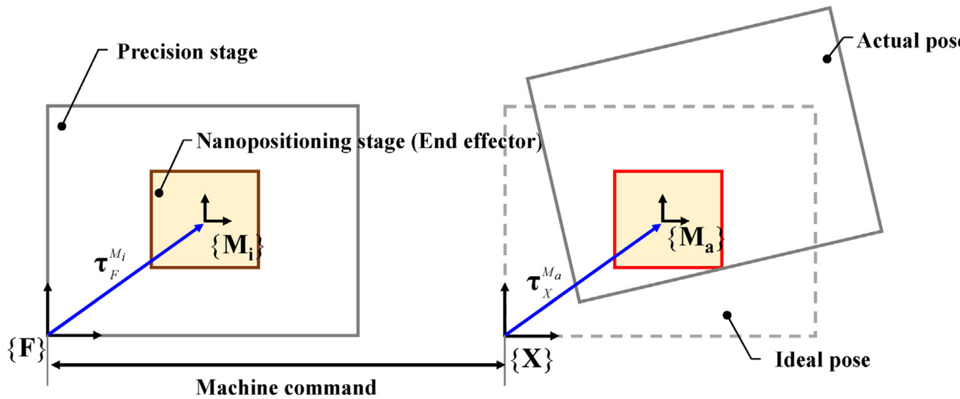

Fig. 1. Objective of the nanopositioning stage.

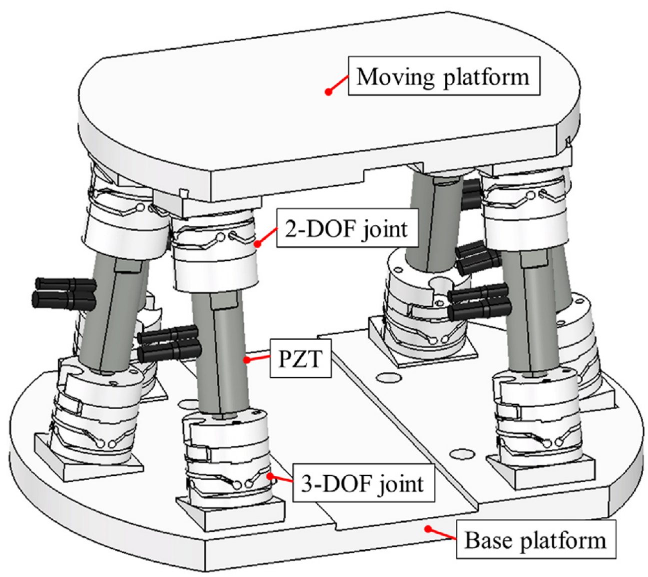

Fig. 2. Configuration of the six-DOF nanopositioning stage.

time-consuming [23]. The roll error of a linear axis cannot be measured with a laser interferometer, and straightness errors are highly sensitive to operator skill. Capacitive sensors are commonly used in precision measurement owing to their high accuracy, and techniques such as single-point, reversal, or the multi-probe method have been developed. The single-point and reversal methods are the simplest to implement, and are typically used to measure the straightness error of a linear stage. The multi-probe method, which uses two or three probes, can be used to measure straightness and angular errors. However, this technique has a high degree of uncertainty and lacks a reference coordinate system.

A nanopositioning stage as compensation mechanism is necessary to compensate for the errors discussed above and to enable high-precision positioning of a long linear stage. The proposed design integrates a linear stage with a high-precision nanopositioning stage. The various nanopositioning stage are developed to improve the positioning accuracy of a linear stage. The magnetic levitation nanopositioning stage that consists of two types VCM actuator with Halbach magnet array is suggested to realize high acceleration and high precision [24]. A three-DOF nanopositioning stage which is driven by Lorentz-force-driven planar motor is developed and the permanent magnet array with unequal thickness are used to increase the force and decrease the force variation [25]. A flexure based three-DOF nanopositioning stage is developed to achieve desired displacements in planer motion and the lever mechanism are used to enhance the displacement [26].

However most of suggested nanopositioning stage are aimed at improving the positional accuracy in the micro travel range. Therefore, it is difficult to apply structurally to compensate the errors (geometric, thermal induced and dynamic errors) of a linear stage with long travel range. Also, the previous suggested fine stages required the external measuring system to control the positional or rational motions. Therefore, it has the problem of large measuring uncertainty by Abbe's error also, it is limited to compensation of some-DOF error because of the measuring system or structure of nanopositioning system. Also previous research focused on the measurement and compensation of specific error sources, such as geometric [27–30] and thermally induced errors [31], as major sources of error. These offline compensation methods are useful when minimizing geometric errors, but are not suitable for use with thermally induced or dynamic errors as they are time-variant sources.

In this paper, we propose a six-DOF nanopositioning stage as a finely tunable stage for the ultra-precise positioning of a linear stage. Geometric, thermal, and dynamic errors are compensated for in real time. Flexure hinge joints are used to position the stage precisely, and a drive component with high structural stiffness and rapid response characteristics is designed to fit the parallel mechanism. The six-DOF errors are measured by a reference mirror, five capacitive sensors, and a linear encoder. The kinematics of the nanopositioning stage is analyzed and the workspace is defined in Section 2. In Section 3, a recursive compensation algorithm is used to improve the performance of the system, and the measurement and compensation of the five-DOF errors are described. The experimental results before and after compensation are evaluated quantitatively by comparing the root mean square error (RMSE) and peak-to-valley (PV) error. Our conclusions are drawn in Section 4.

2. Design of the Six-Dof nanopositioning stage

Linear stages offer a large workspace and fast acceleration. A nanopositioning stage provides high resolution within the micron range with a multi-DOF flexure mechanism driven by PZT actuators. Here, the nanopositioning stage was fitted to the linear stage, as shown in Fig. 1. The relationship between the coordinate system of the linear axis $\{\boldsymbol{X}\}$ and end effector $\{\boldsymbol{M}_a\}$ is constant and independent of machine command, as shown in Eq. (1).

$$\boldsymbol{\tau}_F^{M_i} = \boldsymbol{\tau}_F^{M_a} \quad (1)$$

Compensation of the precision stage's six-DOF errors was realized by combining the drive and measurement components, as shown in Fig. 2. The drive component comprised a base plate,