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Design of a long range nano-scale resolution mechanism*

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Abstract: This paper presents the development of a coarse-fine dual precision positioning stage to achieve long travel range and high accuracy. The fine stage is arranged in series with a coarse stage. The key in the fine stage design is the choice of a toggle mechanism for a tight mechanical loop with high stiffness and compactness. We designed the toggle mechanism for reduction of the displacement to suppress signal noises. The performance of the coarse and fine stages was verified with an optical encoder and capacitive sensor, respectively. The measurement results show that the dual mechanism has a travel range of 1 mm and resolution of 30 nm.

Key words: Coarse-fine dual stage, Nano-scale resolution, Piezoelectric (PZT) actuator
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1 Introduction

The need to manipulate and control miniature objects in nanometer resolution has received considerable attention in the nanotechnology. The compliant mechanisms, composed of flexure hinges and leaf springs, have the advantage of non-backlash and can be monolithically machined to achieve ultra-high precision positioning (Chang and Du, 1998; Chang and Li, 1999; Wang and Chang, 2006; Wu *et al.*, 2008). The limitation of the positioning technique using piezoelectric (PZT) actuators with nanometer resolution often is, however, its short travel range, often as little as a few hundred microns. The drawback has been resolved by different methods, such as the slip-stick (Wang and Chang, 2006), dual servo actuator (Kimiyuki and Goto, 1996; Liu *et al.*, 2003) and use of a magneto-strictive actuator (Yang *et al.*, 2006). Dual stage design (Liu *et al.*, 2003) consists of a coarse stage and a fine stage with two servo-motors in the coarse stage and three PZT actuators being used for fine positioning. The process for direct nano-scale positioning utilizes the electrostatic interactions between the molecules and nano-patterns (Losilla *et al.*, 2008). This paper describe the dual stage that combines a single PZT actuated fine stage on a coarse positioning stage to achieve the nano-scale resolution and large travel range. A toggle linkage is employed to suppress the displacement and increase the signal-to-noise ratio at the nano-scale displacement measurements.

2 Mechanism design

The design of the coarse and fine stages is shown in Fig. 1. The coarse stage is simply an electromagnetic drive motor with the linear ball screw linear stage. On top of the coarse stage, a fine PZT actuator is in-series mounted as the fine stage. The displacement of the whole system is the combined displacement of the coarse and the fine stages. In this study, a linear optical encoder (or is called optical scale) was mounted to measure the linear displacement. To align the optical scale, we mounted a five-degree-of-freedom (5-DOF) stage which is manually operated to adjust and align the geometrical position of the optical grating of the optical scale with respect to the optical

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head. Once the alignment of the optical scale is achieved, the 5-DOF stage is removed. The engineering specification of the coarse positioning stage is listed in Table 1.

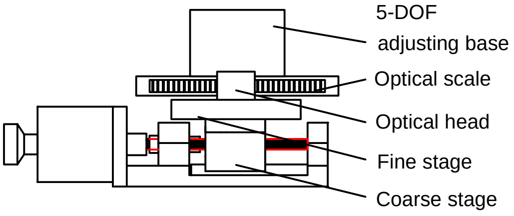

Fig. 1 Schematic design of the dual positioning stage

Table 1 Specification of the coarse stage

Component	Description
Actuator	Step-motor, 2-phase, 50000 step/rev
Transmission	Ball-screw, C3, lead: 1 mm
Guide	Linear guide, ball bearing
Sensor	Optical encoder, resolution 10 nm

Travel range: 10 mm, resolution: 1 μm

The fine positioning stage is illustrated in Fig. 2 and the specification is listed in Table 2. The motion is driven by a multilayered piezoelectric (PZT) actuator (2 in Fig. 2) made by the Tokin Inc., Japan. The longitudinal vibration of the PZT is employed for motion generation, as illustrated by an arrow in Fig. 2. In this case, the motion is toward the flexure joint in the lower direction. The displacement sensitivity of the PZT is 11.6 μm/100 V of the electric potential. The longitudinal vibration is achieved so that the mechanical motion is in parallel to the electrical field. The PZT of 5 mm×5 mm×20 mm is installed in the monolithic steel plate 1 in Fig. 2, such that its shape is formed by use of the electro-discharge-machining (EDM).

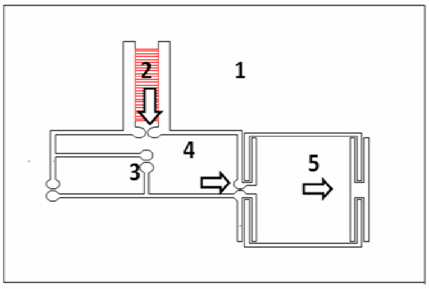

Fig. 2 Design of the fine piezoelectric (PZT) actuated positioning stage using the toggle mechanism

1: steel plate as the structure of fine stage; 2: PZT; 3: flexural joint; 4: toggle linkage; 5: parallel linkage. The arrows indicate the motion direction when PZT is driven by electrical voltage

Table 2 Specification of the fine stage

Parameter	Description
Actuator	Multilayered PZT, 11.6 μm/100 V
Travel range	2 μm
Resolution	10 nm
Transmission	Toggle mechanism, displacement reduction
Joints	Elastic flexure guide, free of clearance
Guide	Parallel linkage, 4 parallel springs

The steel plate 1 in Fig. 2 is machined to perform the motion of two linkages, i.e., a toggle mechanism (4 in Fig. 2) and a parallel mechanism (5 in Fig. 2). The motion provided by the PZT will first transmit to the toggle mechanism with its displacement output orthogonal to the PZT displacement, as indicated by the arrows in Fig. 2. Then, the motion is transmitted to the parallel mechanism which contains four parallel flexural springs, as shown as 5 in Fig. 2. The final displacement is orthogonal to the direction of the PZT motion.

The revolute joints of the mechanism are the flexural hinges shown as 3 in Fig. 2, fabricated by the EDM. The elastic flexural hinges provide the rotation DOF as the revolute joints. The rotation of the links connected by the flexural hinge is achieved by the elastic deformation at the flexural joint. It offers the advantage of freedom from friction, hysteresis and high precision and linearity. The drawback, when rotation occurs, is that the strain energy stored in the flexural hinges will reduce the mechanical power generated by the PZT. Therefore, the design of the linkage requires a detailed calculation of power loss in the strain energy of flexures.

The toggle linkage is a four-bar linkage and the angle controls the displacement amplification or reduction (Fig. 3). We designed the toggle for reduction of the displacement for signal noise suppression. The nature of the structure itself has the advantages of a small mechanical loop and precision motion. The mechanical loop represents the energy flow path from the input member to the output member. A small mechanical loop is desired to minimize the transmission error, increase precision and enhance the mechanical stiffness and response. The toggle linkage is designed by extensive finite element analysis to determine the geometry of the linkage.

The relationship of the displacement ratio of the output and the input, i.e., the amplification of the linkage with the link length of *l* is derived as follows:

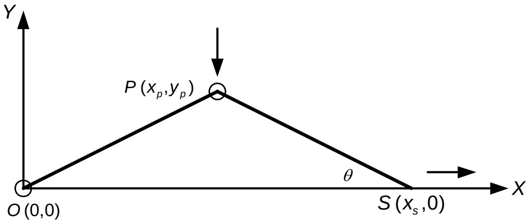

Fig. 3 Illustration of a toggle linkage

$$x_p = \sqrt{l^2 - y_p^2}, \tag{1}$$

$$x_s = 2x_p = 2\sqrt{l^2 - y_p^2}, \tag{2}$$

$$\begin{aligned} \frac{\Delta x_s}{\Delta y_p} &\cong \frac{\mathrm{d}x_s}{\mathrm{d}y_p} = \frac{\mathrm{d}(2\sqrt{l^2 - y_p^2})}{\mathrm{d}y_p} \\ &= \frac{-2y_p}{\sqrt{l^2 - y_p^2}} = \frac{-2y_p}{\frac{x_s}{2}} = -2\tan\theta. \end{aligned} \tag{3}$$

Eq. (3) can be used to find the angle at which the linkage will produce the reduction of the displacement. At the angle of 26.57°, the output displacement will be reduced. On the other hand, the displacement will be amplified.

Before the device is fabricated, the design of the toggle mechanism is assisted by the finite element model (FEM) as shown in Figs. 4 and 5. The 2D-elastic-element modelling is used to construct the model to solve the static deformation and free vibration characteristics. Emphasis is on the angle of the toggle mechanism with respect to the lateral displacement that is to be minimized. We set up an FEM using software ANSYS to analyze rigidity, the maximum displacement, and working frequency of the actuator stage. The actuator stage was modeled using the four-node element. The static analysis result, when the PZT exerts the force into the toggle mechanism, is shown in Fig. 5. The figure shows the deformation of the fine stage under the input voltage of PZT at 100 V. The strain energy at the flexural hinges can be estimated.

3 Experiments and performance

The displacements of the coarse and fine positioning stages are evaluated using their own sensors. The optical encoder and capacitive sensor are used for the coarse stage and the fine stage, respectively (Fig. 6). The relationship of the signals in the optical encoder is shown in Fig. 7. Their engineering specifications are listed in Tables 3 and 4, respectively.

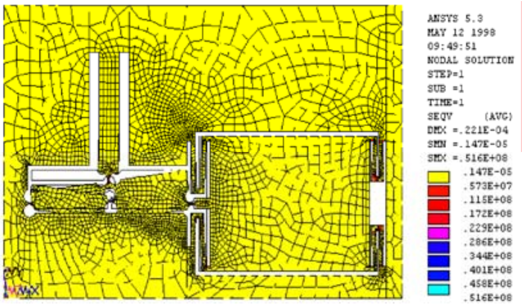

Fig. 4 Design is evaluated by the finite element model. The figure shows the mesh of the finite element model. The deformation of the toggle linkage and the parallel linkage can be solved in response to the motion of the PZT

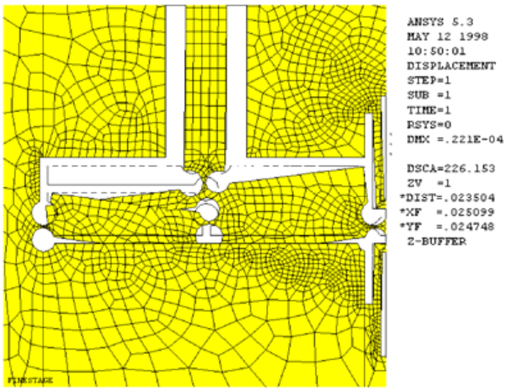

Fig. 5 Enlarged deformation of the toggle linkage calculated by the finite element model

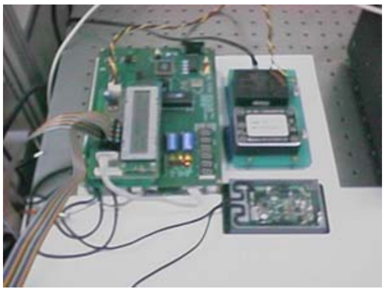

Fig. 6 Optical encoder with the signal processor

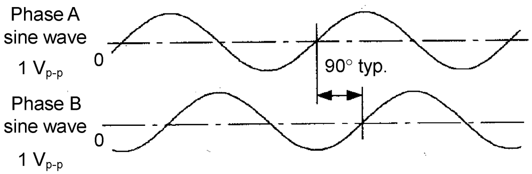

Fig. 7 Relationship of the A and B signals in the optical encoder

Table 3 Specification of the optical encoder

Parameter	Value
Measure length (mm)	150
Grating pitch (μm)	1.6
Resolution (nm)	10
Linear accuracy (μm)	60.3

Table 4 Specification of the capacitive sensor

Parameter	Description
Material	Al
Gain (μm/V)	1.5
Bandwidth (kHz)	1.5
Voltage output (V)	612.3
Linearity (%)	0.05

The high strength steel is chosen as the fine stage (Fig. 8), and is fabricated by EDM. It is then assembled with the coarse stage in series (Fig. 9). Its system block-diagram for experiment is shown in Fig. 10. The drive and feedback signals are integrated in a personal computer through the digital to analogue (DA) converter and analogue to digital (AD) converter.

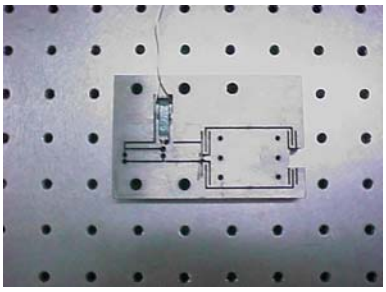

Fig. 8 A prototype piezoelectric actuated fine positioning stage

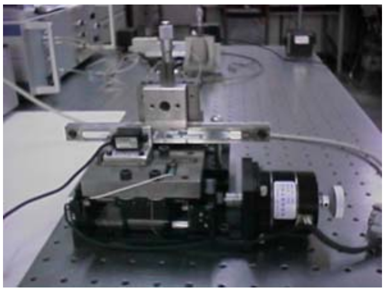

Fig. 9 A photo of the assembled dual positioning stage

The multilayered PZT (5 mm×5 mm×20 mm) containing 144 layers with layer thickness of 108 μm and density of 800 kg/m^3, expands 14.7 μm under 150 V. The first resonant frequency of multilayered PZT ceramics measured by the HP impedance analyzer is 69 kHz.

We applied 20–100 V to drive the PZT and measured the linear displacement of the actuator stage, as shown in Fig. 11. With displacement reduction of the toggle linkage, Fig. 5 shows the displacement of 3.24 μm under the driving signal of 100 V. The hysteresis of the actuator stage was also measured under −40 to 40 V at 2 Hz.

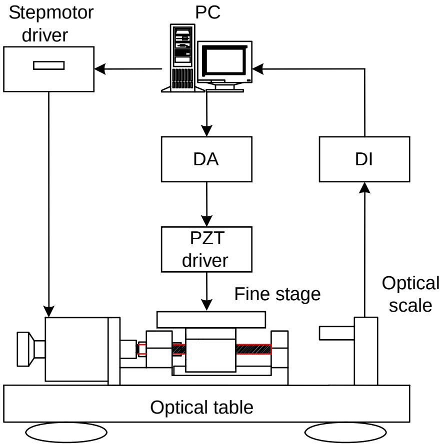

Fig. 10 System block-diagram of the dual positioning stage for experimental study

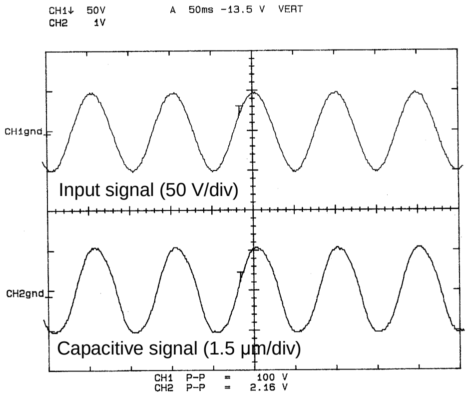

Fig. 11 Measurement result of the fine stage. The upper curve is the electrical voltage to drive the PZT actuator. The lower curve is the displacement measured by the nanometer resolution capacitive sensor

In terms of accuracy of the coarse positioning stage, from the experimental data using the linear optical encoder, a positioning error of 2 μm was found. Fig. 12 shows the measurement curve at the travel range of 1 mm. The detailed investigation of the system integration of the dual stage shows that the fine stage is capable of feeding back the positioning error within 30 nm in the 1 mm travel range.

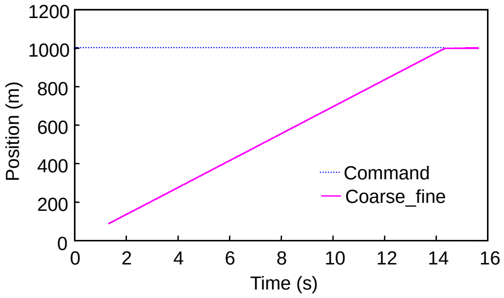

Fig. 12 Measured displacement curve for the coarse stage at displacement of 1 mm by using the linear optical scale

4 Discussion and conclusion

This paper describes the design, fabrication, and experimental results of a long travel positioning stage with nano-scale resolution. The positioning stage includes a course and a fine stage. The fine stage is driven by a multilayered PZT actuator, and is made of a toggle linkage and a parallel linkage. The special design of the toggle linkage to suppress the signal noise in the nano-scale displacement functions well. The effect of the thermal deformation and dynamic fatigue on the performance of the stage should be evaluated next. In this study, the long range of 1 mm is demonstrated. The design, however, can be extended to arbitrary ranges of the coarse motion. With the design's simplicity and high accuracy, applications in long-range nanopositioning, such as precision assembling, atomic force microscope scanning, and micro-nanomachining, are possible.

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