A Large Range XY Flexure Stage for Nanopositioning

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Abstract
This paper presents the design and test results of an XY flexure stage with large ranges of motion and substantially small error-motions. The flexure topology is conceived by means of a systematic and symmetric arrangement of double parallelogram flexure modules. Finite Element Analysis is performed to quantify the flexure stage performance, which is validated by means of experimental measurements. The prototype flexure stage of size 300mm x 300mm exhibits a 5mm x 5mm range with cross-axis errors less than 10microns, and motion stage yaw errors within 5 microradians.

Introduction
Large range XY flexure stages are important in several applications such as semiconductor mask and wafer alignments [1], scanning interferometry and atomic force microscopy [2-3], micromanipulation and microassembly [4], high-density memory storage [5], molecular experiments, and MEMS devices [6]. Since these applications generally require nanometric positioning and pose space limitations, flexure-based motion stages are the optimal bearing choice. Despite several XY stage designs that exist in the literature [7-9], achieving large range of motion has been a challenge.
Recently, some new parallel kinematic XY flexure designs have been proposed [10-11], that are based on a systematic assembly of common flexure building blocks in a fashion that does not overconstrain the primary motions. An understanding of the properties of the building blocks and a symmetric layout results in improved performance measures such as cross-axis coupling, parasitic yaw motions, and actuator isolation. Because of it large motion and high degree of symmetry, one particular configuration was chosen for the purpose of design, fabrication and testing, and is presented in this paper.

Design and Analysis
The XY flexure design presented in Fig. 1 is based on a constraint arrangement that is realized by utilizing the double parallelogram flexure module. The constraint arrangement includes four basic rigid stages: ground, motion stage, and intermediate stages 1 and 2. Intermediate stage 1 is connected to ground by means of a flexure module which only allows relative X translation, and motion stage is connected to intermediate stage 1 such that only a relative Y translation is allowed. Similarly, the flexure module connecting intermediate stage 2 to ground only allows relative Y translation, and that connecting motion stage to intermediate stage 2 only allows a relative X translation. Thus, in any deformed configuration of the mechanism, intermediate stage 1 will always have only an X displacement with respect to ground while Intermediate Stage 2 will have only a Y displacement. Furthermore, the motion stage inherits the X displacement of

Intermediate Stage 1 and the Y displacement of Intermediate Stage 2, thus acquiring two translational degrees of freedom that are mutually independent. Since the Y and X displacements of the motion stage do not influence intermediate stage 1 and stage 2, respectively, the latter provide ideal locations for actuation. Without causing overconstraint, the design is further enhanced by making insightful use of symmetry, which involves adding intermediate stages 3 and 4, and repeating constraint the arrangement described above. Since all the connecting flexure modules are stiff in planer rotation, the rotation of the motion stage is also constrained with respect to ground, and therefore no active motion stage yaw compensation is necessary. Double parallelogram flexure modules are inherently thermally stable and therefore result in a stable overall XY mechanism. Modules with tilted beams may also be consider for improved inline stiffness between the actuator and motion stage.

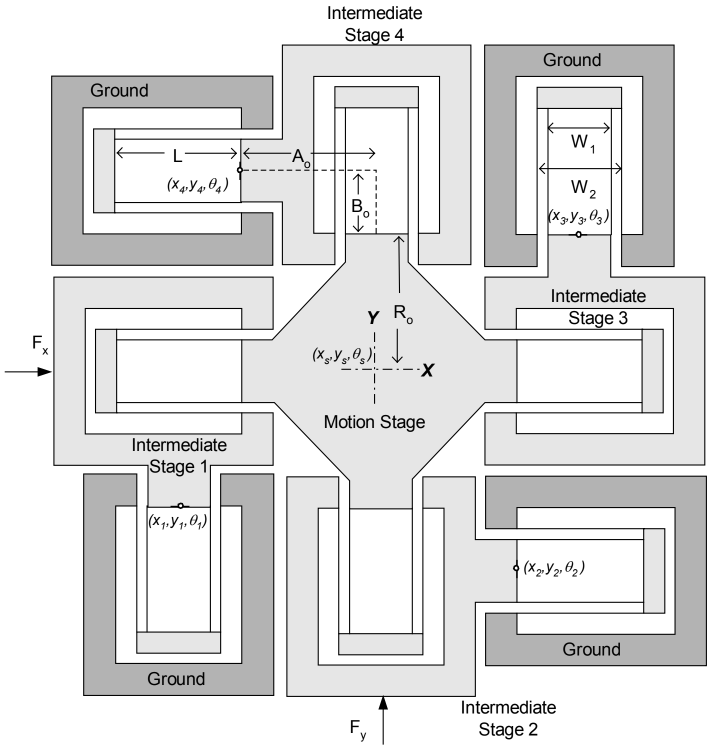

Fig.1 XY Stage Design

A non-linear FEA, which captures the affect of axial forces on the transverse stiffness of a beam and vice versa, is used to predict the design performance in terms of range of motion, over-constraint, stiffness variations, actuator isolation, center of stiffness, cross-axis coupling, and parasitic error motion. A complete closed-form non-linear analysis of this and similar mechanisms is provided in the literature [10].

Experimental Set-up and Results

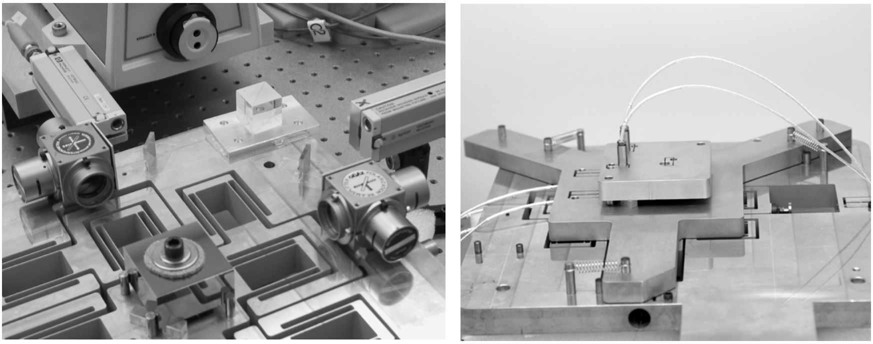

Fig.2 a) Laser Interferometry Set-up b) Capacitance Probes Set-up

A 300mm x 300mm AL6061-T651 prototype XY flexure stage was precisely fabricated using wire-EDM. The experimental set-up was designed so that the stage can be actuated using free weights, motorized precision micrometer, and piezoelectric stacks. Forces were applied along the center of stiffness (COS) axes for the mechanism, which were analytically determined to lie along the X and Y axes in Fig.1. The metrology is set up so that the translations and rotations of the motion and intermediate stages can be measured using plane mirror laser interferometry, autocollimation and capacitance gages as illustrated in Fig.2. The experiments were conducted on an isolation table, and measurements were corrected for temperature and humidity variations. Simultaneous measurements using multiple sensors and successive measurements using different actuators yield a reliable and accurate validation of the predicted properties of the XY mechanism.

The motion stage displacement x_s versus applied force F_x for different levels of F_y is plotted in Fig.3a). This indicates a linearity of less than 0.20% over a 5mm range of travel, and 0.01% over 1mm, without active feedback.

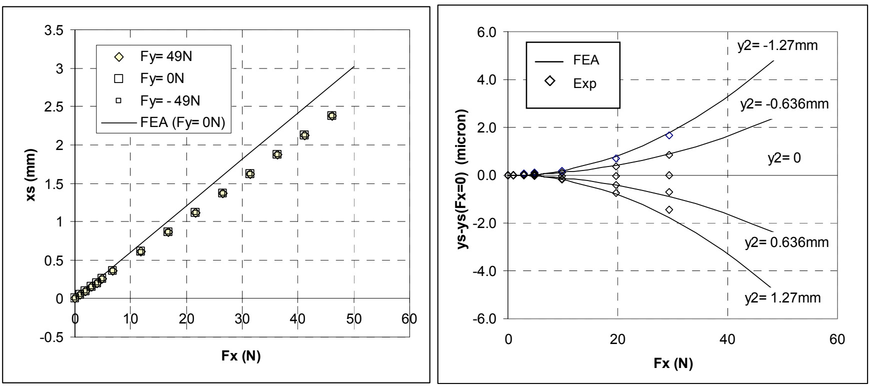

Fig.3 a) Primary Motion b) Cross-axis Error Motion

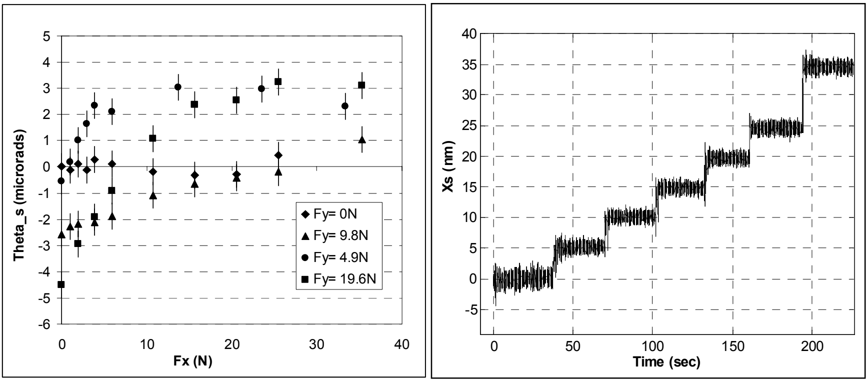

Fig.3 c) Motor Stage Yaw d) Translation of Motion Stage: 5nm steps

Fig.3b) presents the relative Y displacement of the motion stage versus F_x, keeping y_2 fixed at different levels. This indicates cross-axis errors of less than 10 microns over a 5mm range and 1 micron over 1mm, with measurement errors of the order of 50nm. The quadratic trend closely matches analytical predictions. Preliminary measurements of the motion stage yaw are plotted in Fig.3c), and are seen to be within +/- 5microradians without an apparent trend. Finally, incremental translation of the motion stage in 5nm steps, generated by a piezo-actuator and measured using 2nm resolution capacitance gages, is plotted in Fig. 3d).

Conclusion and Acknowledgement

We have presented a new XY flexure design that provides performance levels that exceed the current state of the art. These performance levels have been analytically determined and experimentally measured. Dynamic, thermal and sensitivity analyses along with further stage characterization are currently being pursued. Also, the proposed flexure stage and some of its variants are being developed for applications in nanopositioning for molecular level experiments, meso-machining center, and MEMS devices. The authors would like to thank Dr. Nicholas Dagalakis and Dr. Jason Gorman of NIST, Gaithersburg MD, USA for their support and help in fabricating and testing the flexure stage prototype.

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