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AI and ML-Enhanced Nano Positioning for Large-Scale XY Scanning Applications

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Abstract:

In this study, an XY flexure stage that provides a variety of motion options while reducing incorrect motions is designed and assessed. In the flexure design, the double parallelogram flexure modules are positioned methodically and symmetrically. The performance of the flexure stage is assessed using finite element analysis, and experimental testing is performed to validate the findings. The built-in prototype of the flexure stage has dimensions of 350 mm x 350 mm, a motion range of 7 mm x 7 mm, cross-axis flaw of less than 15 microns, and yaw flaws of less than 5 microradians. For precise applications in domains like semiconductor production, microscopy, and nanotechnology, nano positioning systems are essential. In an XY mechanism, achieving a wide scanning range while preserving nanometer accuracy poses difficulties about mechanical limitations, control accuracy, and structural stability. The basic ideas, importance, and benefits of nano positioning in long-range XY scanning methods are examined in this article. Important design factors, actuation methods, and control schemes required to accomplish high-performance positioning are covered.

Keywords: Flexure stage, FEA, Double Parallelogram Flexure, cross axis flaw.

1. Introduction

This article discusses the value of large range XY flexure stages in light of their use in a variety of processes, such as semiconductor mask and wafer alignments [1], scanning interferometry and atomic force microscopy [2–3], micromanipulation and micro assembly [4], high-density memory storage [5], molecular experiments, and MEMS devices [6]. Since they require nanometric alignment and have space restrictions, flexure-based motion stages are the ideal choice for bearing mechanisms in these applications. The literature has a variety of XY stage designs [7-9], but obtaining a wide range of motion has proven challenging. For contemporary technologies that demand sub-nanometer resolution, precise placement has become crucial. Applications including semiconductor lithography, biomedical imaging, and atomic force microscopy (AFM) frequently use nano positioning devices. Among these, the XY mechanism is essential for offering highly accurate and repeatable two-dimensional positioning capabilities. However, mechanical drift, hysteresis, and thermal expansion are some of the issues that limit the ability of conventional XY mechanisms to achieve both nanometer precision and a wide scanning range. To improve nano positioning performance in applications requiring a wide scanning range, this article explores the developments and methods for getting beyond these restrictions. The cross axis in flexbox runs perpendicular to the main axis, therefore if your flex-direction is either row or row-reverse then the cross axis runs down the columns. If your main axis is column or column-reverse, then the cross axis runs along the rows.

Recent developments in parallel kinematic XY flexure designs [10–11] call for the methodical integration of fundamental flexure building blocks without overtaxing the primary motions. Understanding these building blocks' properties and employing a symmetrical arrangement may considerably improve performance measures including cross-axis link connection, freeloading yaw moments, and actuator isolation. The design, production, testing, and presentation of a specific configuration with a significant motion range and a high degree of symmetry are covered in depth in this work. For large scanning range XY mechanisms, nano positioning is an essential technology for contemporary precision applications. Superior accuracy, range, and stability can be attained by these systems through the integration of high-resolution actuators, sophisticated control systems, and optimized mechanical designs. Future developments in nano positioning offer even greater gains in speed, efficiency, and integration with new applications as material science and nanotechnology continue to progress. New opportunities in industries like high-resolution microscopy, healthcare imaging, and semiconductor manufacturing will be fueled by ongoing research and innovation.

Why Nano Positioning Is Important for a Wide Scanning Range

For many scientific and industrial applications, the capacity to accurately place objects at the nanometer scale over a vast scanning area is essential. Among the important significant factors are:

- Precision manufacturing and nanoscale material characterization depend on high-resolution imaging and fabrication.
- Semiconductor industry: Needed for flaw identification, wafer inspection, and lithography. High-precision microscopy and single-molecule manipulation are made possible by biomedical research. The alignment of optical components in high-precision optical systems is supported by optics and photonics.
- It takes sophisticated actuation and sensor technologies, reliable control algorithms, and well-designed mechanical systems to achieve a greater scanning range while preserving nanoscale accuracy.

Nano positioning's Benefits in XY Mechanisms

- High Precision and Accuracy: For applications needing extremely precise positioning, this solution offers sub-nanometer resolution.
- Large Scanning Range: Allows for precise control while moving over millimeter or centimeter scales.
- Quick Reaction Time: Precise and quick movement is made possible by sophisticated piezoelectric actuators and flexure mechanisms.
- Decreased Mechanical Wear: Friction and wear are reduced by non-contact actuation techniques like piezoelectric or electromagnetic actuation.

- ➢ Compact and Lightweight Designs: Contemporary nano positioning systems improve portability and maximize space utilization.
- ➢ Better Stability and Repeatability: Hysteresis effects and thermal drift are reduced by sophisticated feedback control techniques.

2. XY Mechanism Analysis and Design

The XY stage in Figure 1 uses a flexure design with a constraint configuration of two parallelogram flexure stages. The ground stage, the moment stage, and the middle stages 1 and 2 are the four rigid parts that make up this design. While the connection between middle stage 1 and the motion stage permits relative Y movement, the flexure module connecting middle stage 1 to the ground only permits relative X translation. Similar to this, only relative X translation is allowed by the module connecting intermediate stage 2 to the motion stage, and only relative Y translation is enabled by the flexure module connecting middle stage 2 to the ground. As a result, intermediate stage 1 only moves X in relation to the ground in any distorted configuration of the mechanism, but intermediate stage 2 moves Y. Due to the inheritance of the X displacement from intermediate stage 1 and the Y displacement from intermediate stage 2, the motion stage has two independent translational degrees of freedom. Since the motion stage's Y and X displacements have no bearing on stages 1 or 2, these intermediary stages present the optimal locations for actuation. The method reproduces the previously specified constraint arrangement, adds intermediate phases 3 and 4, and guards against over constraint. The planar rotation stiffness of the flexure modules connecting the stages efficiently limits the rotation of the motion stage with regard to the ground. Therefore, yaw in the motion stage does not need to be actively corrected. The use of double parallelogram flexure modules, known for their intrinsic thermal stability, helps the XY mechanism and adds to the system's overall stability. In order to increase the in-line stiffness between the actuator and motion stage, it is also possible to investigate the addition of inclination beams in the modules.

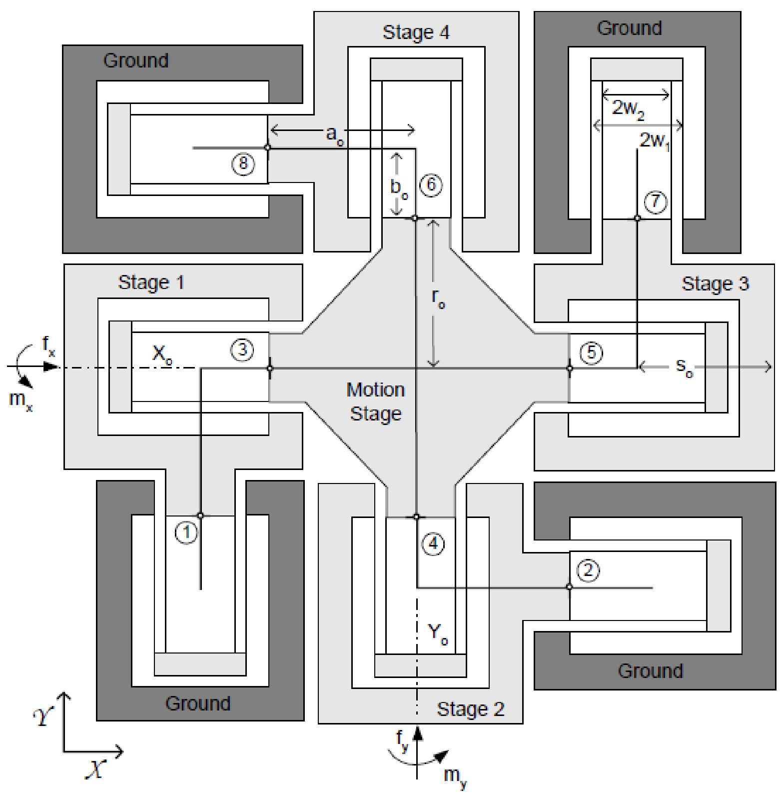

Figure1: Stages of mechanism

A nonlinear finite element analysis (FEA) is used to assess how well the design performs in terms of things like range of motion, over-constraint, stiffness changes, actuator isolation, Centre of stiffness, cross-axis coupling, and parasitic error motion. This study enables a thorough evaluation of the behavior and attributes of the design. This FEA considers the relationship between the transverse stiffness of a beam and axial forces. This mechanism and related ones have been extensively studied using closed-form non-linear methods in the literature [10].

3. Setup of Experimental

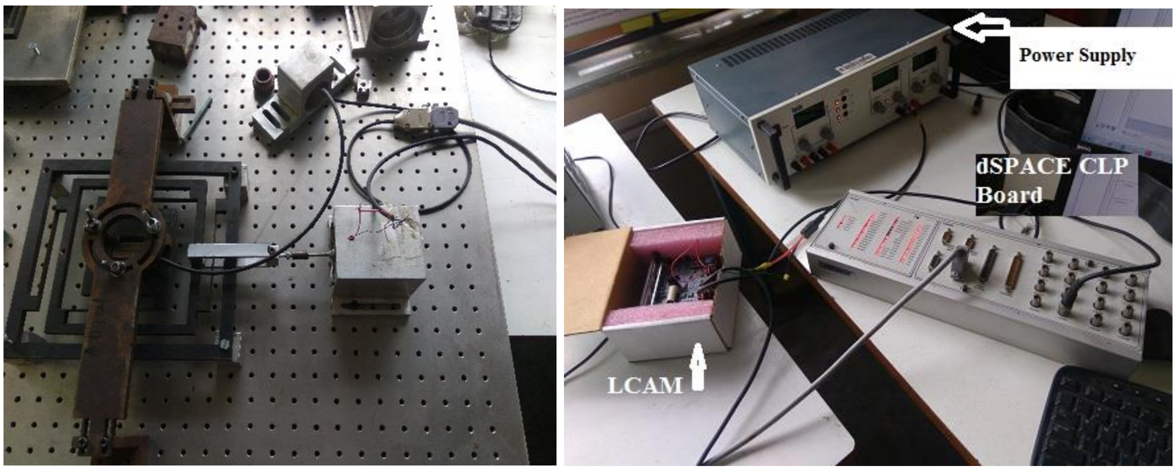

Figure 2 a) Laser Experimental Arrangement b) Setup of Sensors Arrangement

Wire-EDM was used to accurately produce a prototype XY flexure stage constructed of Aluminum that has dimensions of 350mm × 350mm. Laser Experimental Arrangement shown in Figure 2(a) A laser diffraction experiment for determining particle size has a simple setup: Initially, the dispersed particles are directed towards a laser beam. Depending on the particle size, the beam is diffracted at different angles by the particles.[12] The experimental set-up allowed the stage to be moved using piezoelectric stacks, a motorized precision micrometer, and free weights. Setup of Sensors Arrangement shown in Figure 2(b) Analytical calculations were used to determine that the mechanism's center of stiffness (COS) axes, which correspond to the X and Y axes in Figure 1, were in line with each other. Using metrology instruments including autocollimation, capacitance gauges, and plane mirror laser interferometry, the translations and rotations of the motion and intermediate phases were calculated .Setup of Sensors Arrangement Readings were adjusted for variations in humidity and temperature during the trials, which were conducted on an isolation table.[13] Many sensors were used simultaneously, and a series of tests with different actuators were made to consistently and accurately evaluate the values for the XY mechanism.

Figure 3a displays the movement stage displacement (Xs) vs. Force on XY stage applied (Fx) plot for various values of Fy. The graph displays a linearity of less than 0.30% over a 7mm trip range and 0.02% over 2mm in the absence of the need for active feedback.

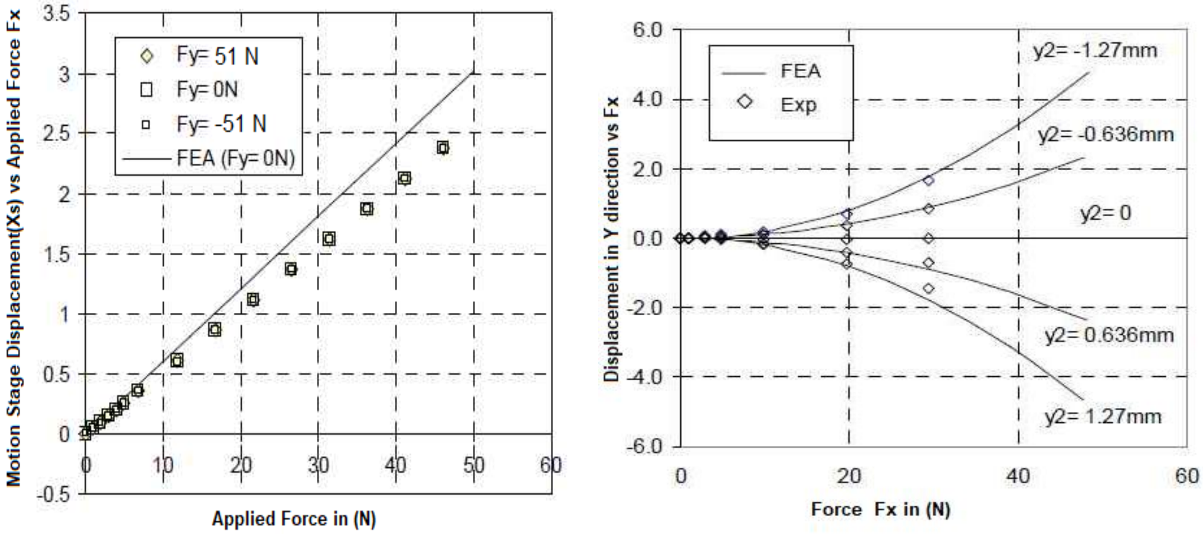

Figure 3: a) Initial Movement b) Error motion in Cross axis

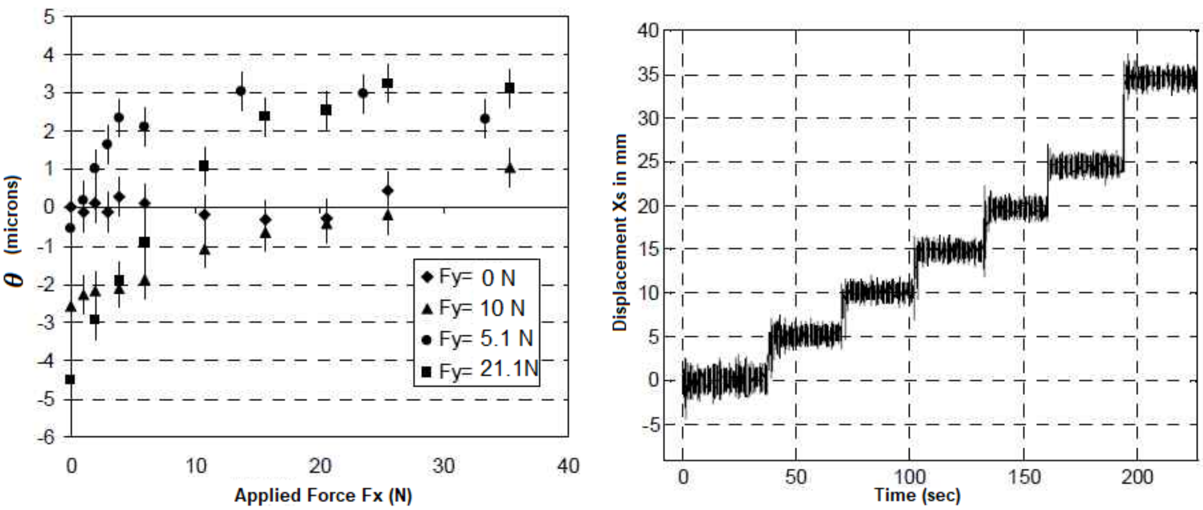

Figure 3: c) VCM Stage d) Motion stage Transformation

Figure 3b depicts the motion stage's relative Y displacement with respect to Fx as the value of y_2 is changed. A measurement error of roughly 60 nm, cross-axis errors of about 15 m over a range of 7 mm, and errors of 2 m over a range of 2 mm are depicted in the figure. The observed quadratic trend closely resembles the forecast analytical projections.[14] Voice Coil Motor (VCM) stages have become essential technology for accomplishing broad scanning range nano positioning for XY mechanisms at the nano level. Electromagnetic actuation is used by VCM stages to provide high precision and quick response times. VCMs function on the direct-drive principle, which lowers mechanical friction and backlash in contrast to conventional stepper or servo motors.

The motion stage yaw is seen in early observations in Figure 3c. The figure displays yaw inaccuracies in the +/- 7 microradian range without any obvious pattern.

Finally, Figure 3d) shows the incremental translation of the motion stage, produced by a piezo actuator, in 7nm increments. With a resolution of 3 nm, capacitance gauges are used to record the readings.

4. Conclusion

Overall, we have developed a unique XY flexure design that outperforms current state-of-the-art performance standards. Analytical calculations and experimental measurements have both been used to evaluate the design's performance. The stage is being further characterized and dynamic, thermal, and sensitivity evaluations are now being performed. The planned flexure stage and its variations are in fact still being developed, and a wide range of applications are included. These include MEMS devices, meso-machining capabilities, and nano positioning in molecular-level research. The results thus far show promise for considerable improvements in positioning accuracy and the widespread application of microscale technologies. The future of these technologies seems bright in light of this development.

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