Design and Experimental Characterization of a Large Range XYZ Parallel Kinematic Flexure Mechanism

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1. Introduction

In this paper, we present the design and experimental characterization of a novel parallel-kinematic flexure mechanism that provides highly decoupled, and therefore large, motions along the X, Y, and Z translational directions. Motivated by applications in multi-axis nanopositioning [1] and kinetic energy harvesting [2], the proposed design inherently accommodates the geometric constraints associated with integrating large-stroke fixed-axis actuators and generators. The motion characteristics of the proposed flexure mechanism are validated by means of extensive finite element analysis as well as experimental measurements. The design and fabrication of a hardware prototype and metrology setup are presented. Analytical and experimental results demonstrate a cross-axis error of less than 3*%*, parasitic rotations less than *2 mrad*, lost motion less than 4*%*, actuator isolation less than 1.5*%*, and no perceptible motion direction stiffness variation over an XYZ motion range of 10 *mm* x 10 *mm* x 10 *mm*.

2. Proposed Design

The proposed design, shown in Fig.1, is based on a systematic and symmetric layout of two kinds of building blocks – rigid stages and parallelogram flexure modules. The rigid stages are labeled as Ground, X stage, Y stage, XY stage, YZ stage, ZX stage, and XYZ stage. This nomenclature is based on the primary mobility of any given stage – the X stage is constrained such that it has mobility along the X direction only, the XY stage is constrained such that it has mobility in the X and Y directions only, the XYZ stage is constrained such that it has mobility in the X, Y, and Z directions, and so on.

In addition to the rigid stages, there are 12 parallelogram flexure modules (PFM), which are grouped by color – green, blue, and red, and serve as motion constraints. The green PFMs (G1 through G4) deform primarily in the X direction and remain stiff in all other directions; the red PFMs (R1 through R4) deform primarily in the Y direction and remain stiff in all other directions; and, the blue PFMs (B1 through B4), deform primarily in the Z direction and exhibit high stiffness in all other directions.

As a consequence of this unique constraint arrangement, the X stage is constrained to move primarily along the X direction guided by PFM G1. Because of the high stiffness of the blue and red PFMs in the X direction, the X displacement of this X stage is passed on to the XY, XZ, and the XYZ stages. But at the same time, the XY and XYZ stage remains free to move in the Y direction because of the compliance of the red PFMs, and the XZ and XYZ stage remain free to move in the Z direction because of the compliance of the blue PFMs.

Given the symmetry of this design, similar motion behavior is exhibited in the other two directions as well. The Y motion of the Y stage is transmitted to the XYZ stage without affecting the latter's mobility in the X and Z directions. And, the Z motion of the Z stage is transmitted to the XYZ stage without affecting the latter's mobility in the X and Y directions. Moreover, the X, Y, and Z stages provide ideal locations for integrating large-stroke fixed-axis X, Y, and Z direction actuators/generators, respectively. A video demonstration of this XYZ flexure mechanism may be viewed here.

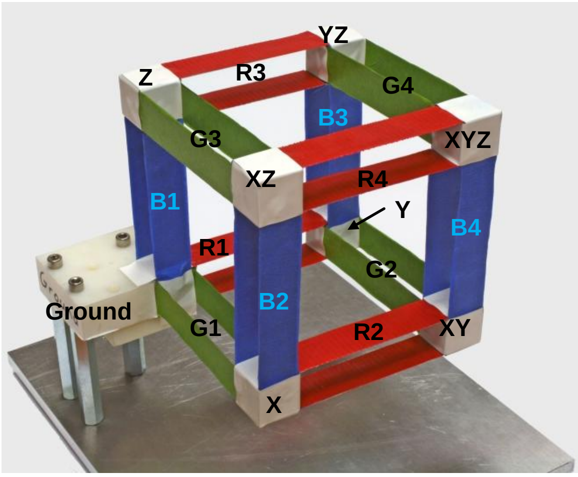

FIG.1 Proposed XYZ Flexure Mechanism Design

3. Motion Performance Analysis

The geometric decoupling, actuator/generator integration, cross-axis errors, parasitic rotations, stiffness variation, and lost motion in the proposed design are investigated by means of finite elements analysis (FEA) in ANSYS. In particular, the role of structural non-linearities [3] in determining these performance metrics is highlighted. This analysis provides the basis for the overall size, detailed dimensions, and material selection of the hardware prototype that is fabricated and tested.

4. Experiment Design and Fabrication

An experimental setup, shown in Fig. 2, was designed and fabricated to validate the predicted quasi-static performance of the flexure bearing.

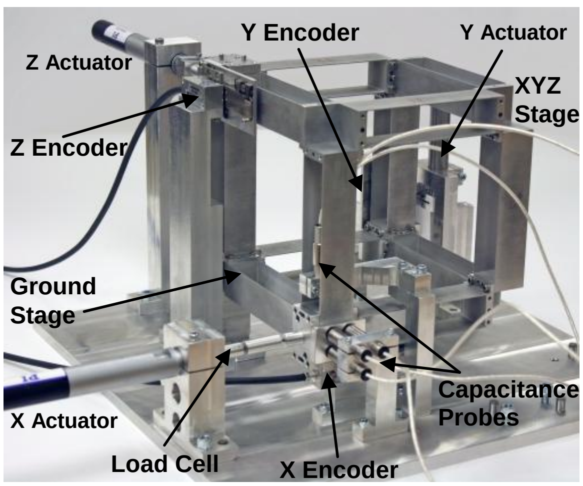

FIG.2 Experimental Setup

The desired measurements include absolute translational and rotational displacements at the input motion stages (X, Y, and Z stage) and the output motion stage (XYZ stage). High-resolution linear optical encoders are well-suited for measuring long range translations of the X, Y, and Z stages. Given the symmetry in the design, the error motions associated with an input stage are measured at the X stage only. Since these error motions are relatively small (≤ 150μm), an arrangement of five capacitance probes is used to measure the Y and Z translation and the three rotations at the X stage. Similarly, the cross-axis coupling and parasitic rotations at the XYZ stage are also measured using multiple capacitance probes.

The X, Y, and Z stages are actuated over their entire motion range (± 5mm) using motorized micrometers. The force applied is measured using miniature load-cells.

5. Results

Figures 3 and 4 present representative FEA results and experimental measurements over an XYZ motion range of 10mm x 10mm x 10mm. This clearly demonstrates the geometric decoupling between the three axes, and the resulting large, unconstrained motion range. In the final version of this paper, we will include analytical and experimental results for all the above-listed motion characteristics of this flexure mechanism over its entire motion range.

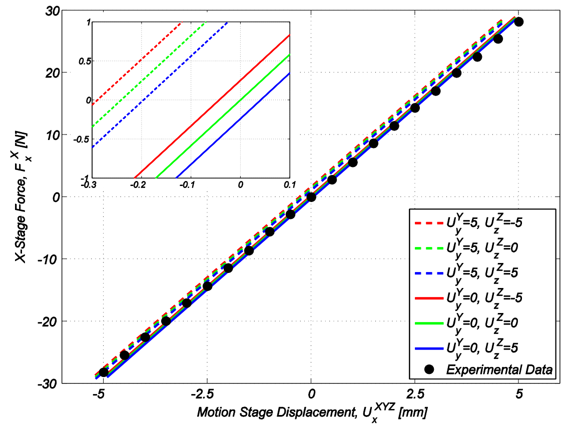

FIG.3 X Direction Force-Displacement Relation

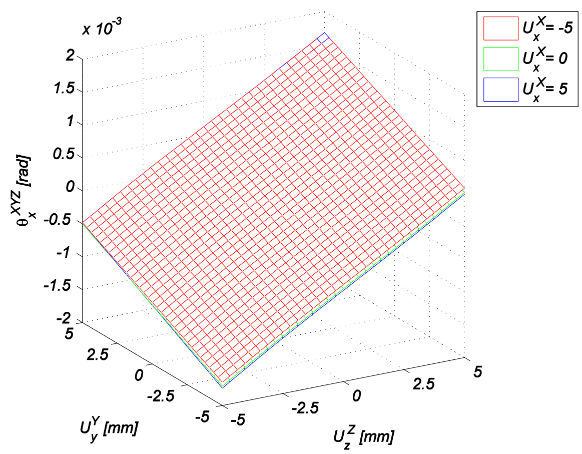

FIG.4 Motion Stage Rotation about X Axis

REFERENCES

[1] Sinno, A., et al., 2007, "Enlarged Atomic Force Microscopy Scanning Scope: Novel Sample-holder Device with Millimeter Range," Rev. Scientific Instruments, 78(9)

[2] Mitcheson, P. D., Rao, G. K., and Green, T. C., 2008, "Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices," Proceedings of the IEEE, 96(9)

[3] Awtar, S., Slocum, A. H., and Sevincer, E., 2007, "Characteristics of Beam-based Flexure Modules," ASME Journal of Mechanical Design, 129(6)