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DESIGN AND FABRICATION OF A THREE-DOF MEMS STAGE BASED ON NESTED STRUCTURES

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ABSTRACT

This paper presents the design, fabrication, and testing of a Micro Electro Mechanical Systems (MEMS) based positioning stage which is capable of generating translational motions along X, Y, and Z axes, respectively. For this purpose, two existing 1 Degree of Freedom (DOF) in-plane positioning stages and one existing 1 DOF out-of-plane actuator are merged into one system for 3 DOF motions. The 1 DOF stage has a platform to embed other systems. For a successful combination of three independent systems, two nested structures are adapted as a serial kinematic mechanism. With nested structures, one 1 DOF in-plane positioning stage is embedded into the other 1 DOF in-plane stage for in-plane translational motions along the X and Y axes. And then, one 1 DOF out-of-plane actuator is embedded for the translational motion along the Z axis. The proposed 3 DOF system has demonstrated ability to generate at least 20 μm along X, Y, and Z axes, respectively. The cross talk between the three axes is also measured and is less than 4 percent of the intended displacement.

*Index terms – MEMS, out-of-plane, electrothermal actuator, eccentric loading
(Some figures in this article are in color only in the electronic version)*

INTRODUCTION

Micro Electro Mechanical Systems (MEMS) based positioning stages are attractive to various applications due to the fact that

they can provide not only small footprints and low cost but also nanometer resolution and tens of micro-meters range of motion.

Several existing MEMS-based positioning stages have focused on in-plane translational or rotational motions and its combination for 3 or more degrees-of-freedom (DOF) motion [1 - 5]. This kind of approach comes from MEMS fabrication techniques which are limited to planar designs, so additional features such as joint hinges are required for out-of-plane or Z axis motion. An XYZ MEMS stage designed for optical scanning and alignment utilizes the coordination of multiple in-plane actuators with a hinge mechanism for out-of-plane motion [2]. Instead of hinges, inclined leaf springs are employed to convert in-plane motion into out-of-plane motion [3]. In these cases, the mechanisms for the Z axis motion are complex to fabricate in general and the friction in the mechanisms reduces its lifetime and causes poor performance.

Free of coordination with in-plane actuators, dedicated out-of-plane actuators for Z axis motion have been developed and adapted for XYZ motion by utilizing a focused ion beam (FIB) milling operation [4] or wafer bonding [5]. With the dedicated Z actuator, the electrostatic actuator generates 1.1 μm displacements at 240 V driving voltage which is similar to its in-plane X or Y axes motion [4] or a 3.5 μm out-of-plane displacement at 14.8 V driving voltages and 25 μm in-plane displacement [5]. Those existing XYZ MEMS stages have their own limitations: (a) due to the electrostatic actuator, its driving voltages are relatively bigger than the Complementary metal-oxide-semiconductor (CMOS)-compatible range, and (b) its Z displacement is in the range of a few micro-meters or relatively smaller than its X or Y directional displacement.

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With dedicated Z actuators, the relationship between three independent actuators should be established via appropriate kinematic mechanisms. One of the commonly used kinematic mechanisms is parallel kinematic mechanism (PKM) [6]. In the PKM, an end-effector has links to all actuators. One of the popular links is parallel chains to avoid any rotational errors. With a PKM, the range of motion decreases to the intersection of all the actuators involved and the coupled motion is still left. In addition, fabrication of parallel chains for the Z axis is still challenging with existing MEMS approaches. Another mechanism commonly used in conventional manufacturing is a serial kinematic mechanism (SKM) [7]. In an SKM, each component in the system is connected to only two neighboring components. An actuator is designated for each axis and the combination of three actuators with the serial kinematic mechanism is able to generate 3 DOF motions. Each actuator has no mechanical links with the others, so it is expected to have no coupled motion between them and no obstacles to reduce its range of motion.

Various MEMS actuators have been adapted for positioning stages [1, 5, 7]. Commonly used actuators are electrostatic [1, 5] or electrothermal [7, 8]. The electrostatic actuator has wider bandwidth and better energy efficiency than the electrothermal actuator, but the electrothermal actuator has

a smaller footprint, CMOS-compatible driving voltage, and millinewton level force generation [8].

This paper presents the design and fabrication of an XYZ MEMS positioning stage which is capable of generating translational motions along X, Y, and Z axes. Due to their having a range of more than tens of microns along the X, Y, and Z axes, electrothermal actuators and a serial kinematic mechanism are selected. Two existing in-plane 1 DOF motion stages and one existing out-of-plane motion stage are utilized for XYZ motion. The demonstration with fabricated devices shows a range of motion tens of μm without acceptable coupled errors.

DESIGN AND ANALYSIS

The proposed XYZ MEMS stage consists of two in-plane stages and one out-of-plane actuator. Two equivalent in-plane 1 DOF stages are selected from previous research due to the fact that it has a platform to utilize for a SKM [7, 9]. Figures 1(a) and 1(b) show a computer aided design (CAD) schematic diagram of the chosen single DOF stage. The stages in Figure 1(a) (called the X stage) and Figure 1(b) (called the Y stage) are aligned with the X and Y axes, respectively. The Y stage is embedded into the platform in the X stage for in-plane X and Y translational motions. An out-of-plane electrothermal actuator,

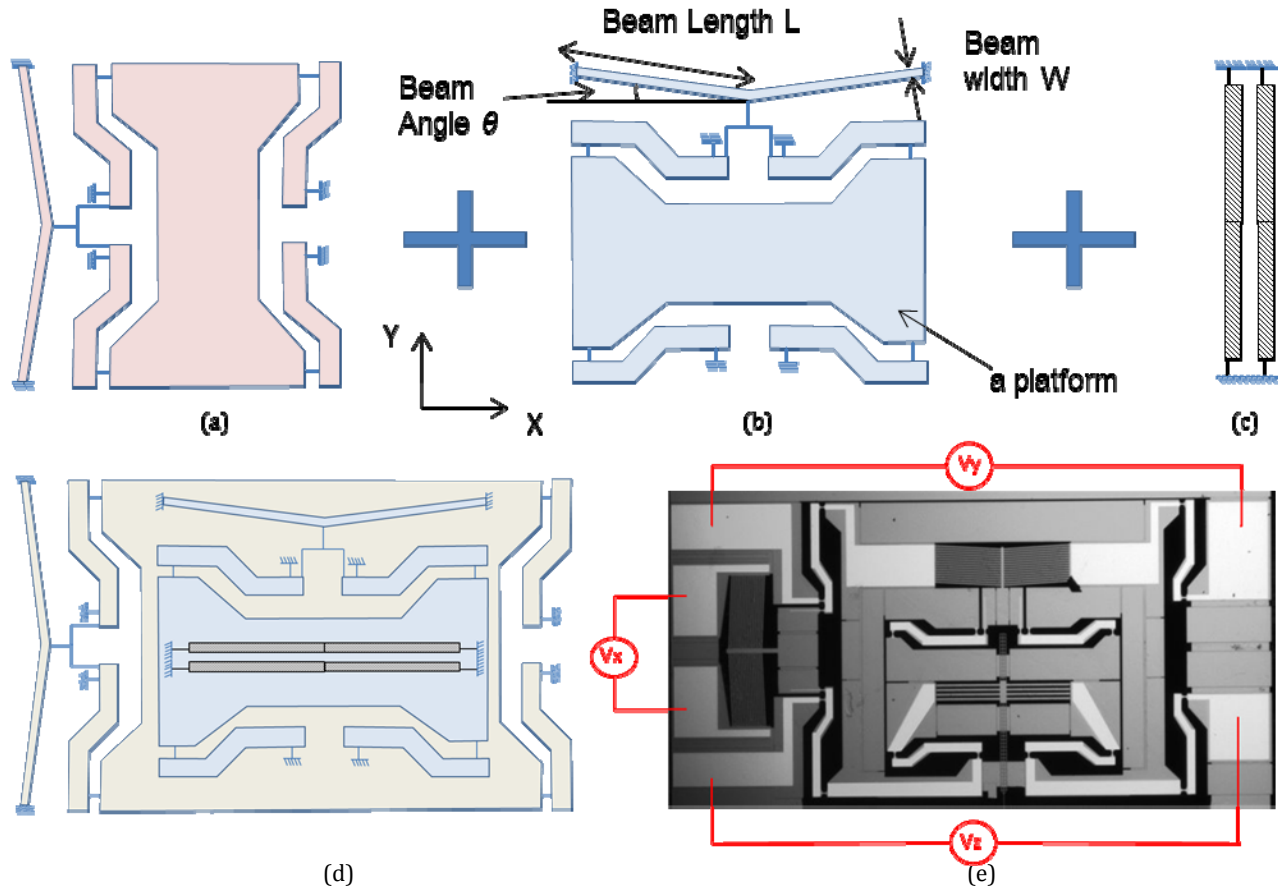


Figure 1. a schematic diagram of the XYZ MEMS stage and its fabrication; (a) X stage; (b) Y stage; (c) Z axis actuator; (d) combination of the three independent systems for XYZ stage; (e) a fabricated device based on (d)

shown in Figure 1(c) (called a Z actuator) is embedded in the platform in the Y stage for a translational motion along the Z axis. Details about the Z actuator are in [10]. The main reasons to select this actuator are: (a) it can be fabricated based on the standard Silicon on Insulator-Multi User Multi Process (SOI-MUMPs) [11] without significant modification and (b) this actuator can generate at least 20 μm displacement. These three separate components are mechanically merged together via two nested structures as a SKM and the final design is shown in Figure 1(d). The fabricated device is shown in Figure 1(e), where the driving voltage V_x is connected to the two pads for the X stage, V_y for the Y stage, and V_z for the Z actuator. The connections for V_y and V_z utilize links and flexures surrounding the platform in the X stage and the Y stage, respectively. The chip size is 4 mm x 7 mm.

1. Design of the in-plane stage

The adapted X and the Y stages consist of an electrothermal actuator, four links, and a platform, as shown in Figure 1(b). For low acceleration these stages can be approximated as two springs in a series. With this serial connection, the expected displacement of the moving platform can be expressed as:

$$\Delta U_{\text{platform}} = \frac{F_{\text{actuator}}}{K_{\text{platform}}} \quad (1)$$

where, U_{platform} , K_{platform} are the displacement and the stiffness of the platform, respectively. F_{actuator} is a force generated by the actuator to move the platform and can be expressed based on beam theory as:

$$\Delta U_{\text{platform}} = \frac{F_{\text{actuator}}}{K_{\text{platform}}} \quad (2)$$

where, α is the coefficient of thermal expansion of silicon, ΔT_{ave} is the average temperature over the actuator, E is the Young's modulus of silicon, and W , T , L , and θ are beam width, thickness, length, and angle, respectively. The average temperature generated by Joule heating in the actuator can be found [12] and expressed as:

$$\Delta T_{\text{ave}} = \frac{P}{K_{\text{actuator}}} \quad (3)$$

The stiffness of the electrothermal actuator can be expressed [13] as:

$$K_{\text{actuator}} = \frac{EWT^3}{12L} \quad (4)$$

where I is the area moment of inertia. The stiffness of the stage can be expressed as:

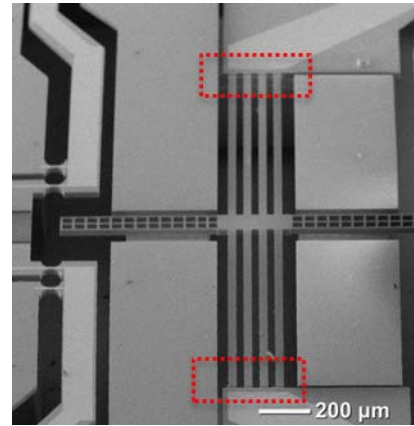
$$\Delta U_{\text{platform}} = \frac{F_{\text{actuator}}}{K_{\text{platform}}} \quad (5)$$

where, n is the lever ratio, m is the number of the flexure hinges used in the target platform, and $L1$ is a link length. C_z is the angular compliance about the Z axis of the flexure hinge and is derived by the Paros and Weisbro formula [14].

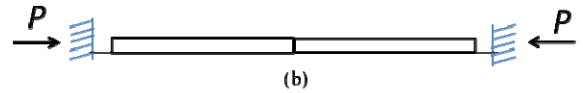
$$\Delta U_{\text{platform}} = \frac{F_{\text{actuator}}}{K_{\text{platform}}} \quad (6)$$

Based on equation (6), the expected displacement of the target platform can be expressed by a square of the driving voltage. Based on all equations described above, all the design parameters are determined and listed in Table 1 below.

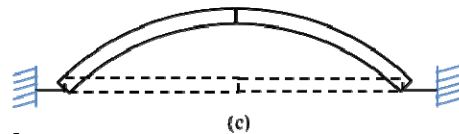
2. Design of the out-of-plane actuator



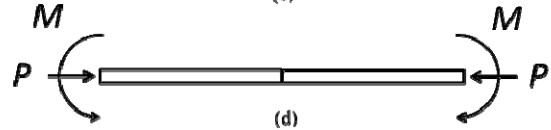
(a)



(b)

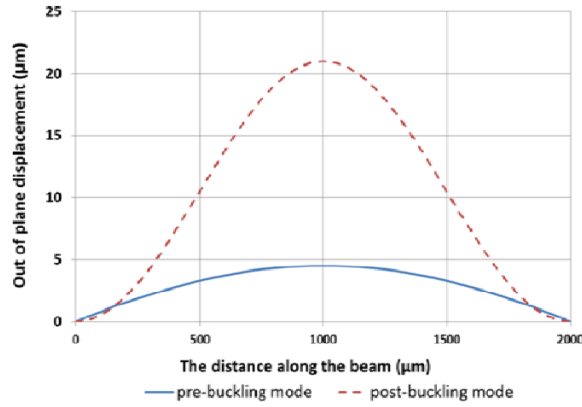


(c)

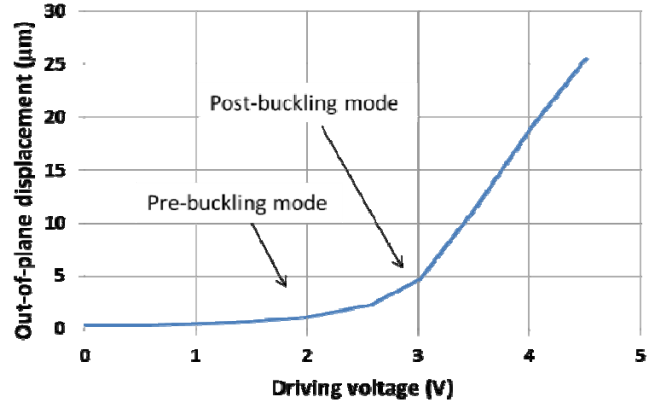


(d)

Figure 2. the Z actuator; (a) fabricated out-of-plane actuator; (b) a schematic diagram of the actuator; (c) expected mechanical behavior during operation; (d) converted free-body diagram based on (b)



(a)



(b)

Figure 3. the Z actuator; (a) expected deformation profile of the out-of-plane actuator at pre- and post-buckling mode; (b) experimental results

The Z actuator is composed of a pair of notches and beams and shown in Figure 2(a), where the Z actuator is embedded into the proposed system. The notches at both ends are indicated by red boxes in Figure 2(a) and the schematic diagram of the Z actuator is shown in Figure 2(b). The beams with notches convert Joule heating into an eccentric load. This eccentric load deforms the beam convex shape at the pre-buckling mode and shown in Figure 2(c). After a pre-buckling mode, the actuator keeps generating out-of-plane motion at post-buckling mode.

The eccentric load P can be converted into one centric load and a moment as shown in Figure 2(d). With this converted free-body diagram, the expected deformation profile at pre-buckling mode can be expressed [15] based on its fixed-fixed boundary conditions.

$$y = e \left[\tan \left(L \sqrt{\frac{P}{EI}} \right) \sin \left(\sqrt{\frac{P}{EI}} x \right) + \cos \left(\sqrt{\frac{P}{EI}} x \right) - 1 \right] \quad (7)$$

for driving voltage ≤ 3 V

where, P is the eccentric load and e is the distance from the central line of the beam to the middle of the notch. With higher driving voltage (more than 3 V in the proposed actuator), the beam begins to buckle and post-buckling becomes dominant. By assuming fixed-fixed boundary conditions, the deformation profile can be expressed [16] as:

$$y = H \left(1 - \cos \frac{2n\pi}{L} x \right) \quad \text{for driving voltage} > 3 \text{ V} \quad (8)$$

where, H is the amplitude of the post-buckling mode, which is indeterminate. This is due to the fact that equation (8) comes from a linearized approximation of the real governing equation of the beam elastic curve. With measured value H from the experiments, the expected deformation profiles at pre- and post-buckling mode beam displacement are plotted in Figure 3(a). The relationship between the out-of-plane displacement and the driving voltage is obtained from

experiments and shown in Figure 3(b). Buckling starts at 3 V with the current design and its out-of-plane displacement accelerates at post-buckling mode.

Based on equations (6), (7), and (8), the design parameters for each component are selected and listed in table 1.

Symbol	Design parameters	Values
W	Beam width of the in-plane actuator	22.3 μm
n	Number of the in-plane actuator	15
θ	Beam angle of the in-plane actuator	3.99 $^\circ$
T	Beam thickness of the in-plane actuator	30 μm
L	Beam length of the in-plane actuator	1000 μm
p	Notch depth of the out-of-plane actuator	15 μm
W_1	Beam width of the out-of-plane actuator	33 μm
L_1	Length of the link connected to the platform	1000 μm
m	Number of flexure hinges utilized in the platform	8
R	Lever ratio of the platform	10/1

Table 1. The list of the design parameters

MICRO-FABRICATION

The proposed MEMS XYZ stage is fabricated on both sides of a silicon-on-insulator (SOI) wafer using mainly Deep Reactive Ion Etching (DRIE). The fabrication process follows SOI-MUMPs [11] and consists of two etchings on the top side, one etching on the bottom side, and metal depositions for electric pads and lines. The SOI wafer used in the fabrication consists of a 30 μm thick device layer (top side), a 400 μm thick handle layer (bottom side), and a 2 μm thick buried oxide layer. Details are shown in Figure 4.

Figure 5 shows some fabricated features related to electric issues. Figure 5(a) shows the electric connection to the Y stage or the Z actuator over the flexure hinge. With this connection, all electric connections to the Y stage and the Z actuator can be controlled outside the X stage. In addition, to avoid any electric coupled motion between stages and the actuator, each actuator is electrically isolated from platforms with physical gaps as

shown in Figure 5(b). The top side has gaps, which hold their shape by additional features beneath them. These additional features, such as blocks, are made from the bottom side silicon. A built-in probe is attached to the Z actuator for future applications and shown in Figure 5(c).

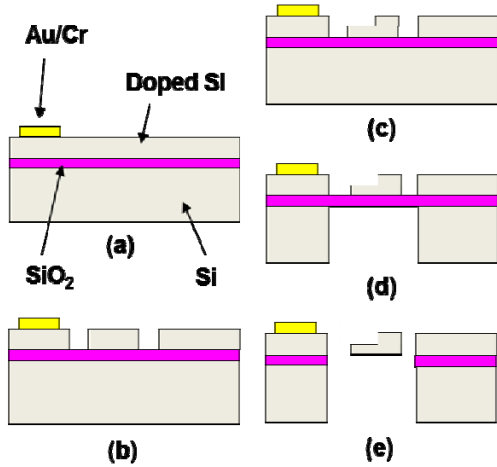


Figure 4. Fabrication sequence: (a) metal deposition for electrical connection; (b) first etching for the main structures on the top side; (c) second etching for the Z actuator on the top side; (d) third etching on the bottom side to open the bottom side of the devices; (e) the removal of the buried oxide layer with buffered hydrofluoric acid (B.H.F.) to release the stage

EXPERIMENTAL RESULTS

1. The range of motion and its coupled motion

The range of motion and its coupled motion are experimentally measured with fabricated XYZ stage samples. The measured ranges along the X, the Y, and the Z axes are plotted in Figure 6. The displacement of the X and Y stages and the Z actuator are measured at 23.9 μm , 25.3 μm , and 21.2 μm , respectively, for driving voltages 8 V, 7 V, and 6 V, respectively. With less than 10 V, each DOF is able to generate at least 20 μm displacements from this experiment. The relationship

between a driving voltage and its displacement shows the pattern described in equation (6): the displacement is proportional to the square of the driving voltage. The in-plane X stage is identical with the in-plane Y stage except the platform size, but the mechanical behavior of the Y stage is slightly different from the X stage. This comes from the difference in the thermal boundary condition. The Y stage is connected via four links to the X stage which is directly linked to the fixed ground. In this case, the Y stage tends to maintain a higher temperature than the X stage with a same driving voltage. The minimum step size in the in-plane motion depends on the electric devices and sensors employed for this system. With an optical microscope, the 1 μm step was repeated. Previous experiments on this design, however, demonstrated that a 50 nm step size was possible [9].

Table 2 summarizes the coupled motion or unwanted motions along X, Y, or Z axes during operation. When one stage or actuator is in operation, the coupled motions along the other two axes are measured at the same time. The coupled motions occurring at the Z actuator by the actuation of the X and the Y stages are relatively smaller than the others, because the Z actuator does not have any platform and, furthermore, is stiffer than the others. But, the Z actuator causes 4.1 % coupled motion to the X stage, because the beams in the Z actuator are parallel with the X axis.

The test results show that the proposed system is capable of generating at least 20 μm displacement along the X, Y, and Z axes with less than 4.1 percent coupled motion.

2. The frequency response

Frequency response of the proposed XYZ stage is measured experimentally along X, Y, and Z axes, respectively. For in-plane X-and Y-axes, an Agilent¹ Fast-Fourier-Transform (FFT) dynamic analyzer is utilized. The response is measured with an intensity-based laser reflectometer. More details on the experimental setups are given in [17]. Figures 7(a) and 7(b) show the frequency response results along X and Y axes. The first oscillatory mode resonance of the X stage occurs at 680 Hz and the corresponding mode resonance of the Y stage occurs at

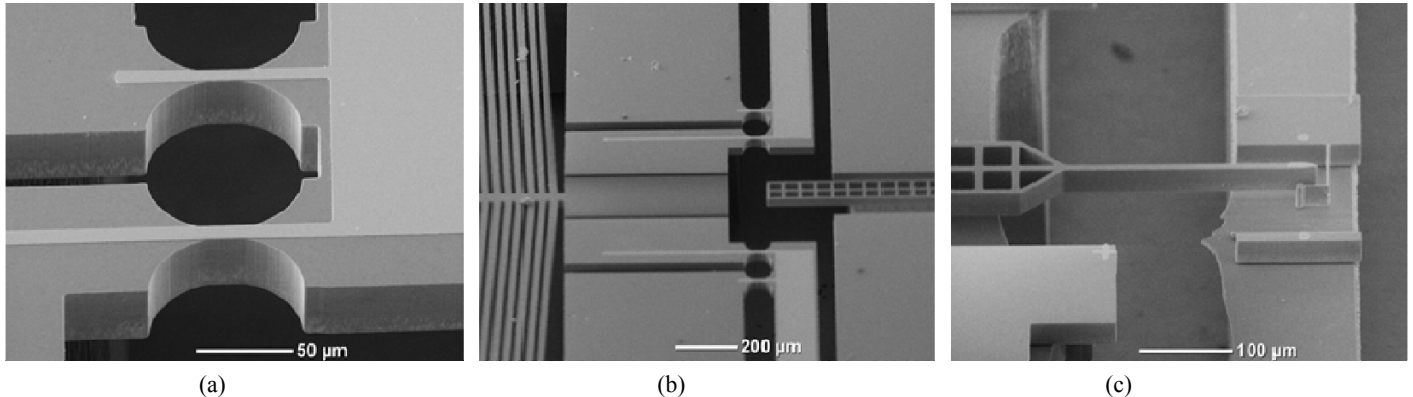


Figure 5. (a) an electric connection over a flexure hinge; (b) an electric isolation between an actuator and a platform; (c) a built-in probe for future application during operation

¹ Certain commercial equipment is identified in this paper to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the equipment identified is necessarily the best available for the purpose.

approximately 1.05 kHz. Since the X stage supports the Y stage and the Z actuator, it is more massive and thus has a lower resonant frequency than that of the Y stage, although they are almost identical in design.

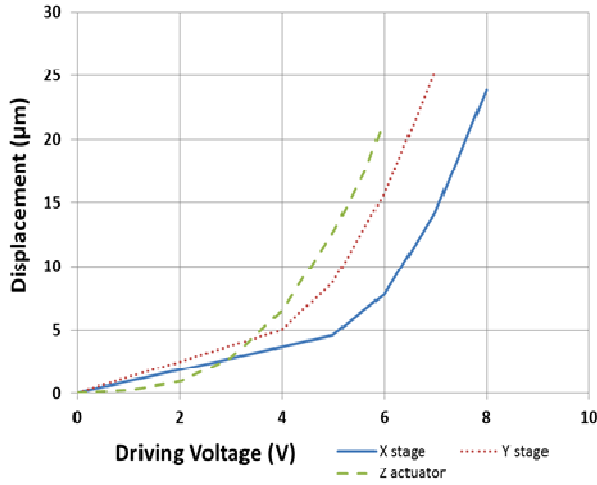


Figure 6. Range of motion along X, Y, and Z axes versus driving voltage

Actuation		Coupled motion					
axis	displacements	X		Y		Z	
		displacements	ratio	displacements	ratio	displacements	ratio
X	23.9 μm	-	-	0.8904 μm	3.7 %	0.007 μm	0.02 %
Y	25.3 μm	0.4593 μm	1.8 %	-	-	0.0161 μm	0.06 %
Z	21.2 μm	0.9185 μm	4.1 %	0.4595 μm	2.0 %	-	-

Table 2. Experimental displacement and cross talk error results between X, Y, and Z axes

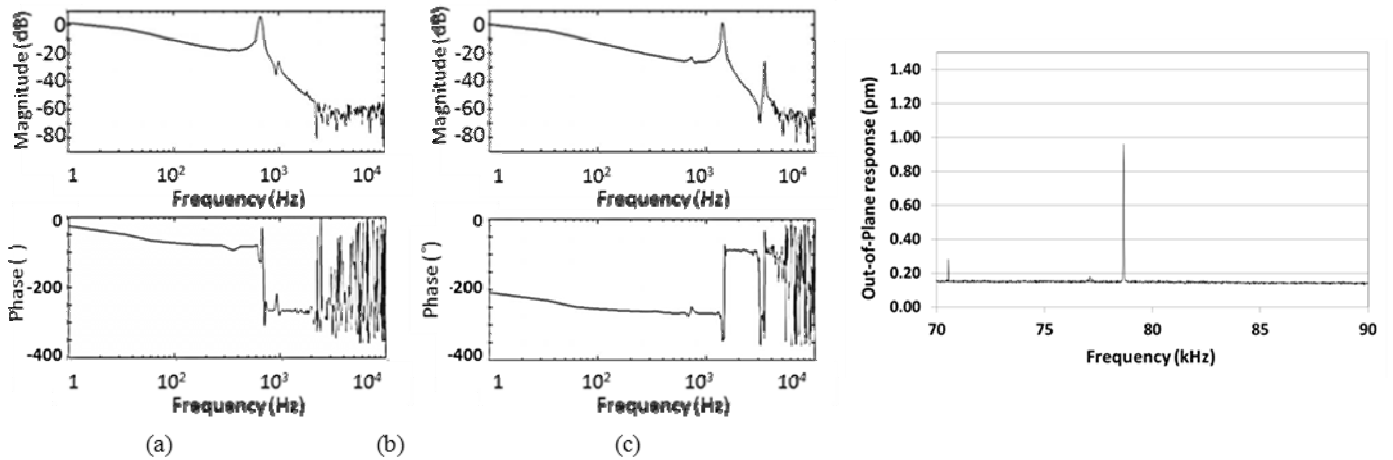


Figure 7. Frequency response graphs for; (a) the X stage; (b) the Y stage; (c) the Z stage

The frequency response along the Z axis is measured by a Polytec¹ MSA-500 Micro System Analyzer [18]. By integrating a microscope and a scanning laser Doppler vibrometer, this analyzer measures the frequency response for out-of-plane motion. Figure 7(c) shows its frequency response along the Z axis. The first oscillatory mode resonance of the Z axis is near 78.3 kHz, which is similar with its finite element analysis

(FEA) result. The frequency is much higher than the other two because the Z stage does not have any platforms.

CONCLUSION AND DISCUSSION

This paper describes an XYZ MEMS nanopositioning stage capable of producing translational motions along X, Y, and Z axes. The proposed system is implemented by nested structures and based on a serial kinematic mechanism. For this purpose, two 1 DOF in-plane stages are adapted as the X and the Y stages and an out-of-plane actuator is selected as the Z actuator. With two nested structures, all three independent systems are merged into a single system for XYZ motion. The merged system forms a serial kinematic mechanism, so the Z stage is embedded into the Y stage. The Y stage is then embedded into the X stage. This system is fabricated based on standard SOI MUMPs [11].

The nanopositioner demonstrated 23.9 μm x 25.3 μm x 21.2 μm range displacements along X, Y, and Z axes with 8 V, 7 V, and 6 V driving voltages, respectively. These are not their maximum allowable ranges of motion. After careful study on fatigue, failure, or plastic deformation, the maximum allowable range of motion needs to be measured again. During operation,

the coupled motions were also measured and found to be less than 4.1 % of the associated motion. Special features for electric isolation and backside holding structure should be carefully evaluated to reduce coupled motion. The frequency response along X, Y, and Z axes was also measured and found to have oscillatory mode resonances at 680 Hz, 1.05 kHz, and 78.3 kHz, respectively.

The in-plane 1 DOF stage utilized in the proposed system is over-constrained for in-plane motion, so any unwanted motion for in-plane motion can be eliminated by this structure. But there are no such mechanisms in the Z actuator, so a guiding mechanism or constraining mechanism for Z axis motion is needed.

The dual nested structures for an SKM can be utilized for further applications such as micro-grippers or embedded active feedback sensors by replacing the Z actuator with grippers or piezoresistive sensors.

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