# Development and Testing of a XYZ Scanner for Atomic Force Microscope

Kunhai Cai[1,2], Xianbin He[1], Yanling Tian[1,2], Xianping Liu[2], Liangyu Cui[1]

[1] Key Laboratory of Mechanism Theory and Equipment Design of Ministry of Education, Tianjin University, Tianjin 300072, China
[2] School of Engineering, University of Warwick, Coventry CV4 7AL, UK

*Abstract*—**Atomic force microscopy (AFM) is a widely used tool in nano measurement and manipulation techniques. However, a traditional AFM system suffers from the limitation of slow scanning rate, due to the low dynamic performance of piezoelectric positioners. As an important part of AFM system, scanner will have a significant impact the result of the scanning imaging and operation. It is well know that high-speed operation of an AFM are increasingly required, and it is also a challenge for the researchers. In this paper, we proposed a parallel kinematic high-speed piezoelectric actuator (PZT) XYZ scanner. The design is aimed at achieving high resonance frequencies and low cross-coupling. The developed stage consists of a parallel kinematic XY stage and a Z stage. The Z stage is mounted on the central moving platform of the XY stage. To achieve the design objective, several parallel leaf flexure hinge mechanisms, arranging symmetrically around the central moving platform of the XY stage, are utilized to provide large stiffness and reduce cross-coupling. For the Z stage, a symmetrical leaf flexure parallelogram mechanism is adopted to achieve high resonance frequencies and decoupling. Then, finite element analysis (FEA) is utilized to validate the characteristics of the XYZ scanner. Finally, extensive experiments are conducted, demonstrating feasibility of the proposed scanner.**

*Keywords*— **XYZ scanner, Mechanical design, High resonance frequency, Coupling error, Testing**

## I. INTRODUCTION

Atomic force microscopy (AFM) is a widely used tool in nano measurement and manipulation techniques [1, 2]. As an important part of AFM system, scanner will have a significant impact the result of the scanning imaging and operation. Conventionally, piezoelectric tube scanners are the most widely used scanner in commercial AFMs, because it has excellent resolution, simple structure, easy to install and configure. However, a traditional AFM system suffers from the limitation of slow scanning rate, due to the low dynamic performance of piezoelectric positioners. It means that high-speed operation of an AFM is increasingly required, and it is also a challenge for the researchers. These factors include: the low resonance frequency of the piezoelectric tube scanner and the cross coupling error of the piezoelectric tube scanner. Therefore, it should be search another scanner to replace the conventional piezoelectric tube, one have high resonance frequencies and accuracy.

In the past few years, base on flexible hinge structure, several XYZ AFM nanopositioning stages have been reported [3-5], which consists of a XY stage and a Z stage. A number of commercial AFMs has appeared in the market that are equipped with flexure-based nanopositioning platforms [6, 7]. In addition, Schitter et al [8] presented a novel scanner for high-speed atomic for microscopy, which enables scanning speeds three orders of magnitude faster than the conventional AFMs. A high-speed atomic force microscopy (HS-AFM) has recently been established by Watanabe et al [9], which was used in video imaging of dynamic processes in live bacterial and eukaryotic cells. Li et al [10] proposed the design, analysis, and testing of a parallel-kinematic high-bandwidth XY nanopositioning stage driven by piezoelectric stack actuators. Klapetek et al [11] presented a large area high-speed measuring system, which enables generating nano-resolution scanning probe microscopy data over $mm^2$ regions.

In life sciences, AFM is the most commonly used as a nanotool for various measurements; high-resolution imaging of biological samples and so on. Toshio Ando [12] believes that AFM was expected to play a role in visualizing dynamic biological processes at high spatial resolution because AFM is only the method capable of directly visualizing vital biological samples in aqueous solutions. However, this expectation could not be met by the low imaging rate. Therefore, the development of high-speed AFM is very urgent for biological applications.

In this paper, we proposed a parallel kinematic high-speed XYZ scanner. The design is aimed at achieving high resonance frequencies and low cross-coupling. To achieve the design objective, several parallel leaf flexure hinge mechanisms, arranging symmetrically are utilized to provide large stiffness and reduce cross-coupling.

## II. MECHANICAL DESIGN AND MODEL VERIFICATION

### A. Mechanical design

The proposed XYZ scanner consists of a XY stage, a Z stage, a base, three piezoelectric actuators (PZTs). The assembly view of the scanner shown in Fig. 1. In the proposed XY stage, the central moving platform (where the Z stage is attached) is connected to four linkages through four parallel flexure mechanisms, and four linkages are connected to the frame through another eight parallel flexure mechanisms. Due to the symmetric mechanical structure, the stage behavior in the X and Y -axis are the same. The Z stage is also designed with a parallel flexure mechanism. The end-effector of the Z stage is connected to the fix frame through four leaf-spring hinges. Four leaf-spring hinges are located at the same circle with the separation angle of 90°, so that the end-effector of the Z stage can only moves along the Z-axis without cross-axis coupling error.

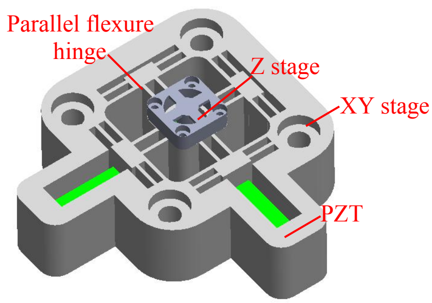



Fig. 1 3D solid model of the scanner

*B. Model verification*

Finite element analysis (FEA) is conducted to validate the established models and obtain further insights into the static and dynamic characteristics of the developed XYZ scanner. The commercial finite element software ANSYS is utilized to perform the analyses. The material for the scanner is chosen as Aluminum 7075-T6 with a density of 2770 kg/m$^3$, a Young's modulus of 71 GPa, and a Poisson's ratio of 0.33. Both of the XY and Z stages are bonded together. In order to improve the computational accuracy, the mapping mesh method is adopted. The mesh is strictly controlled in the areas of flexure hinges, where the large deformation is generally occurred.

In order to investigate the motion characteristics of the system, the static characteristic analysis is carried out. The in-plane stiffness of the scanner should be high so as to increase the rejection capability against external disturbances. The analysis results shows that the linear stiffness without and with PEAs installed are 25.63, 25.72 and 10 N/μm in the X, Y and Z direction, respectively. However, the out-of-plane stiffness of the XY stage is a key factor in determining its capacity of resisting disturbance. An out-of-plane stiffness of 222 N/μm is achieved.

The dynamic characteristics of the scanner are investigated and the results are shown in Fig. 2. The first two mode shape are moved along the X- and Y-axis with the frequency of 4995.1 Hz and 4996.3 Hz, respectively; the third and fourth mode shape rotate and moved along the Z-axis, with the corresponding frequencies of 13822 Hz and 25815 Hz, respectively. If the PZTs are installed, the corresponding frequencies will increase. It means that the system has good dynamic characteristic.

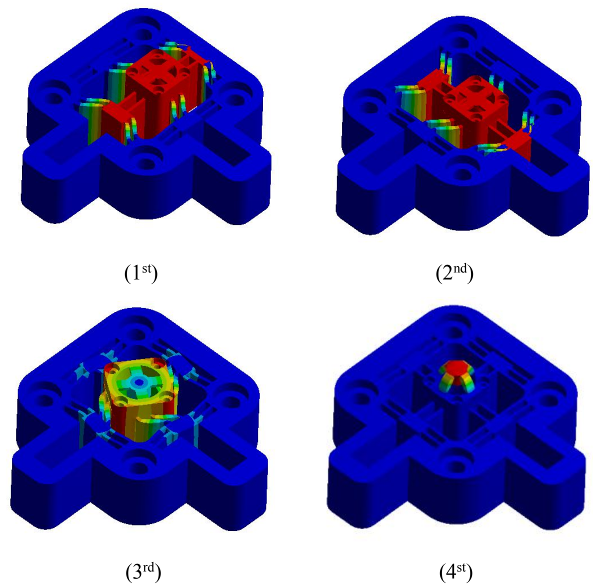



Fig. 2 First four modal of the scanner

## III. Experimental and Results

The developed prototype of the scanner is shown in Fig. 3. The top and bottom surfaces are fabricated on a milling machine, respectively. Subsequently, artificial aging is utilized to release the residual stress. Computer numerical control (CNC) assisted wire electrical discharge the machining (WEDM) technique is utilized to manufacture all the flexure structures. During the WEDM fabrication process, low-speed feeding is selected to guarantee the machining accuracy, and a fabrication tolerance of 2 μm is achieved. Both of the XY and Z stages are bolted together.

The performance of the proposed scanner was systematically evaluated. As shown in Fig. 4, the scanner is actuated by the THORlabs (PZS001 6 mm × 7 mm × 20 mm) piezoelectric stack actuators which are driven by the THORlabs (MDT693A) voltage amplifier with the gain of 7.5~15. There are four strain gauges placed on each of the actuator to form a full Wheatstone bridge. The strain of the actuator is measured by the strain gauge and processed with an am- plifier. A pair of PI (D-050.00) capacitive sensors with a measurement range of 50 μm and a resolution of 0.01 nm is

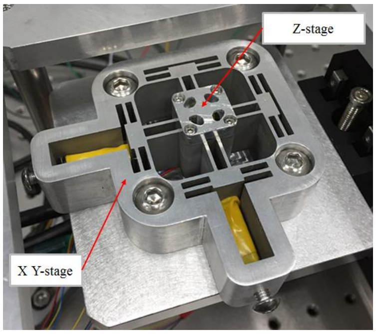



Fig. 3 The prototype of the scanner

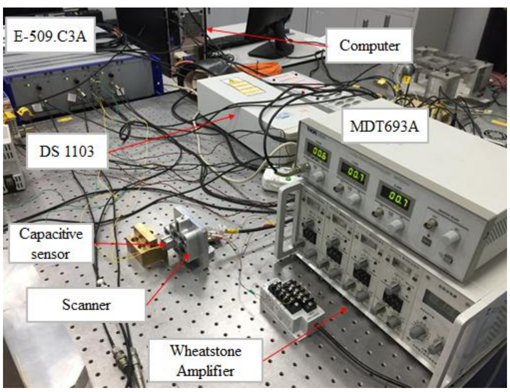
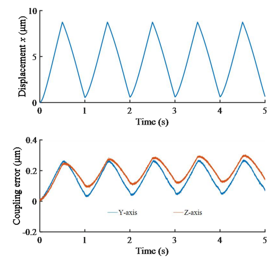



Fig. 4 Experimental setup of the system

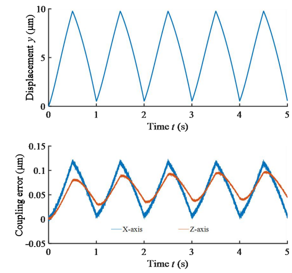
mounted on the Z-stage to capture the motions of the nanopositioner before being amplified by a PI (E-509.C3A) amplifier. The mounting direction of the sensor is related to the different axes. The control signal of the motions and the data acquisition task are implemented using a dSPACE (DS 1103) R&D board which is communicated with the computer through PCI bus.

### *A. Motion range and coupling error*

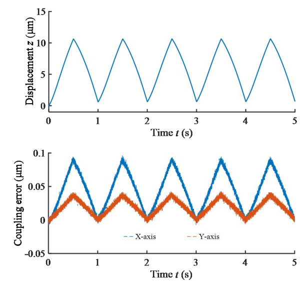
The effective motion range is validated, by applying a 1 Hz sawtooth voltage signal to each PZT, and the displacement in three working axes are measured. A motion range of 8.7 μm is achieved for the X-axis positioning as shown in Fig. 5(a), meanwhile, the induced parasitic motion in Y- and Z-axis are depicted, which are about 2.9% and 2.2% of the primary X-axis motion range, respectively. Similarly, the test result of motion range in Y-axis is shown in Fig. 5(b). In addition, the induced parasitic motion in Y-axis is also depicted, it reveal that the maximum crosstalk is 0.12 μm in X-axis and 0.1 μm in Z-axis, which are about 1.2% and 1.03% of the primary Y-axis motion, respectively. a motion range of 10.6 μm is achieved for the Z-axis positioning as shown in Fig. 5(c), the induced parasitic motion in X- and Y-axis are depicted, which are about 0.88% and 0.39% of the primary motion range, respectively.



(a) X-axis



(b) Y-axis



(c) Z-axis

Fig. 5 The result of motion range

### *B. Step respond and resolution*

The step responses of the system are investigated, and the step responses in the X- , Y- and Z- axes directions are shown in Fig. 6. The result shows that the 2% settling time of the step responses are 13, 15 and 10 ms, respectively.

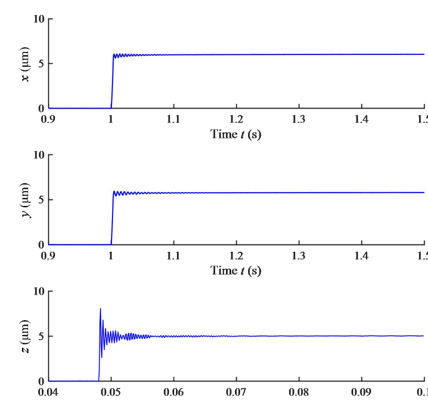


Fig. 6 The result of step respond

Precision motion is tested. As can be seen in Fig. 7, the minimum resolutions are clearly resolved from the multi-step response experiment, which as regards three stability measures are 9 nm in the X-axis, 8 nm in the Y-axis and 8 nm in the Z-axis, respectively.

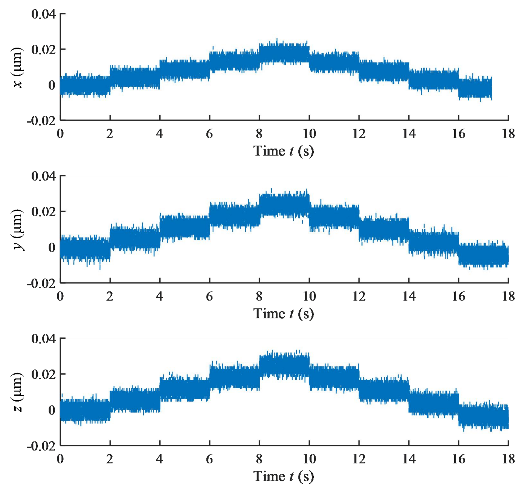



Fig. 7 The result of resolution

## IV. Conclusions

This paper presents the design of a parallel kinematic high-speed piezoelectric actuator (PZT) XYZ scanner, which consists of a parallel kinematic XY stage and a Z stage. Both manufactured using the wire electrical discharge machining (WEDM) technology. The Z stage is mounted on the central moving platform of the XY stage. In addition, finite-element analysis (FEA) is utilized to validate the static and dynamic characteristics of the proposed scanner, the system with the lowest resonant frequency of 4995.1 Hz, which ensures that the system has good dynamic characteristic. Finally, extensive experiments are conducted, the test results show that the scanner has an effective workspace of 8.7 μm × 9.7 μm × 10.6 μm. The cross-axis coupling ratio of the proposed scanner is below 2.9%, indicating effective decoupling performances. Meanwhile, the motion resolution is less than 9 nm. According to the step respond test, high-speed respond can be confirmed.

## Acknowledgment

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## Conflict of Interest

The authors declare that they have no conflict of interest.

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