Application of piezoelectric actuator in series nano-positioning stage

Qian Lu and Xifu Chen
School of Mechanical Engineering, Yancheng Institute of Technology, Yancheng City, China

Abstract
The existing nano-positioning stages are driven by the piezoelectric ceramics, which have features of high accuracy and resolution, but the traditional positioning stage could not meet the requirement of large working space because the displacement of the piezoelectric ceramics is only tens of microns. To solve the contradiction between high accuracy and large working space, a novel non-resonant piezoelectric linear actuator, which adopted the two parallel v-shaped stators as the double driving feet, was proposed, and both its working principle and structure were discussed in detail. The actuator was used to drive the positioning stage directly to obtain the performance of nano-positioning and large working stroke. The experiment results show that the resolution of the actuator is 0.015 μm, and its stable maximum motion speed is 17.4 mm/s, while the degree-of-freedom of step resolution of each nano-positioning stage is 0.018 μm, 0.016 μm, and 0.3 μ rad, respectively. Compared with the traditional positioning stage, the nano-positioning stage driven by the actuators directly also has excellent working stroke. The key performance of both high resolution and large working stroke of the nano-positioning stage was realized based on different motion modes of only one piezoelectric actuator.

Keywords
Nanometer positioning, piezoelectric actuator, nano-positioning stage, large working space

Introduction
With the rapid development of the nanometer technology,1 microelectronics industry,2 bioengineering,3,4 aerospace,5 and other disciplines, research on nano-scale is getting more and more important, and many disciplines have entered nano-scale. Therefore, the devices with nano-scale operational accuracy have become the key...
equipment. In the field of optical devices and optical engineering, the multi-degree-of-freedom (DOF) nano-positioning stage is becoming the key performance equipment. The requirements of the operation stage or the positioning stage are becoming much more strict, and the most important index of performance is high resolution and large working stroke. Precision positioning stage with multi-DOF has been studied widely in recent years. The current nano-positioning stages are almost driven by the piezoelectric ceramics, which has the advantages of high accuracy and resolution, but its displacement is only tens of microns, and it is difficult to meet the needs of large working space. To make up the defects of small displacement of piezoelectric ceramics, the displacement amplification mechanism is arranged between the piezoelectric ceramics and the positioning platform. The lever amplification mechanism, differential amplifier, and bridge type amplification mechanism are the most frequently used. However, it is noteworthy that the displacement magnification mechanism reduces the positioning accuracy while enlarging the working stroke of the piezoelectric actuator. Therefore, the requirements of high accuracy and large working space become a contradiction.

To solve this contradiction and make the nano-positioning stage satisfy the requirements of large working space and high accuracy at the same time, many scholars proposed and studied the serial-parallel positioning stages. In addition, Sun and Dong proposed the flexure hinge with large displacement, and applied it in the parallel positioning platform; Li and Li studied the new flexible parallel mechanism with 3-P(4S) based on the flexure hinge with large displacement; Xu developed a XY positioning mechanism with large working space by taking use of the variable stiffness principle; Shayya et al. proposed the 5-DOF parallel positioning manipulator by the prismatic actuator; Shan et al. discussed the vertical precision positioning system using ultrasonic linear actuator; Olfatnia et al. designed the electrostatic comb driver for the application of positioning mechanism with large working space. Summarizing the above mentioned studies, the serial-parallel positioning platform, or the new designed flexure hinge with large displacement, or the new actuator with large working space, the applications of them are still limited because of the large structure or the complex control model.

Aiming at solving the contradiction between the high accuracy and large working space, a nano-positioning stage, driven directly by the piezoelectric actuator, was proposed by making use of the two working modes of the piezoelectric actuator. Specifically speaking, the two working modes were the continuous motion mode and the step motion mode. The continuous motion mode could realize the macro-motion with large working space and the step motion mode is responsible for the nano-positioning with high accuracy. Obviously, the transmission chain is shortened greatly, the responsible speed is improved, and the control is also simplified. Therefore, the nano-positioning stage could satisfy both the requirements of high accuracy and large working space. The development of optical, biomedical, and other technologies has placed increasing demands on the accuracy and working range of positioning stages. The positioning stage with capabilities of high-precision and large working range can greatly improve the engineering application
The method proposed in this article, which adopted non-resonant piezoelectric actuators to directly drive the positioning mechanism and achieve the high resolution and large working range, would provide a new way for the engineering application of precision actuation and control technology.

Design of the piezoelectric actuator

Structure design

Considering that the traditional single v-shaped stator structure had a well-known performance, the v-shaped stator was used in the optimized piezoelectric actuator, which worked at the non-resonant frequency and had better stable resolution. The non-resonant piezoelectric linear actuator adopted two parallel v-shaped stators to form the double driving feet, and the two parallel stators were fixed into the guide box by assembly screws. The guide box was responsible for restraining the motion of other axes. The single stator was composed of the driving foot, piezoelectric stack, cushion block, bracket, elastic beam, pre-tightening bolts, and clamping device. The cushion block was used to adjust the clearance between the piezoelectric stack and the driving foot. The elastic beam and the pre-tightening bolts could support the suitable pre-tightening force to guarantee the piezoelectric stack the best performance. The structure of the stator was shown in Figure 1.

There were four piezoelectric stacks, marked as a1, a2, a3, and a4, respectively, and were divided into two groups. In the actual arrangement, the piezoelectric stacks a1 and a2 were fixed in the stator 1 and the piezoelectric stacks a3 and a4 were fixed in the stator 2. Therefore, the driving feet of the two stators could generate motion only if the two groups of piezoelectric stacks were driven by the suitable excitation signal.
Working principle

According to the literature, under the excitation of sine signal, the displacement curve of piezoelectric stack is similar to the sine wave, and the deformation of piezoelectric stack is linear to the driving voltage in the low-frequency band. Therefore, the excitation of sine signal that excited onto the four piezoelectric stacks was as follows

\[
\begin{align*}
    u_1(t) &= A(1 + \sin \omega t) \\
    u_2(t) &= A(1 + \cos \omega t) \\
    u_3(t) &= A(1 - \sin \omega t) \\
    u_4(t) &= A(1 - \cos \omega t)
\end{align*}
\]  

(1)

where \( A \) is the voltage amplitude and \( \omega t \) is the phase.

However, the deformation of the piezoelectric stack is

\[
\delta = \alpha u
\]

(2)

where \( \alpha \) is a constant coefficient, \( u \) is the voltage value.

Obviously, the displacement of the four piezoelectric stacks was as follows

\[
\begin{align*}
    \delta_1(t) &= \alpha A(1 + \sin \omega t) \\
    \delta_2(t) &= \alpha A(1 + \cos \omega t) \\
    \delta_3(t) &= \alpha A(1 - \sin \omega t) \\
    \delta_4(t) &= \alpha A(1 - \cos \omega t)
\end{align*}
\]

(3)

The parameter \( t \) of formula (3) could be eliminated, and the conclusion could be obtained as follows

\[
\left\{ \begin{array}{l}
[\delta_1(t) - \alpha A]^2 + [\delta_2(t) - \alpha A]^2 = \alpha^2 A^2 \\
[\delta_3(t) - \alpha A]^2 + [\delta_4(t) - \alpha A]^2 = \alpha^2 A^2
\end{array} \right.
\]

(4)

Because the piezoelectric stacks 1 and 2 were fixed in the same stator, and the piezoelectric stacks 3 and 4 were fixed in the other stator, formula (4) shows that the trajectory of the driving foot of every stator is ellipse. The two groups of piezoelectric stacks were placed orthogonally in space, and the excitation signal of the two groups of the piezoelectric stack differed 90° in phase, thus any one of the two driving feet could touch and drive the mover alternately at any time. The excitation signal was shown in Figure 2 and the movement principle of the stator in one period was illustrated in Figure 3.

There were four stages in the stators’ movement in one period, and the movement principle of stators in one period was discussed in detail.

The first stage (0–1/4T): The piezoelectric stack 1 vibrated longitudinally, and it deformed from \( \alpha A \) to the maximum deformation of \( 2\alpha A \). The piezoelectric stack 3 vibrated longitudinally, and it deformed from \( \alpha A \) to the minimum deformation of 0. Therefore, the driving foot 1 contacted the mover, while the driving foot 2 separated away from the mover. The piezoelectric stack 2 vibrated horizontally, and it
deformed from $2\alpha A$ to $\alpha A$ along the right direction. At this stage, the mover was driven to the right.

The second stage ($1/4T$–$1/2T$): The piezoelectric stack 1 vibrated longitudinally, and it deformed from $2\alpha A$ to $\alpha A$. The piezoelectric stack 3 vibrated longitudinally, and it deformed from $0$ to $\alpha A$. Therefore, the driving foot 1 still contacted the mover, while the driving foot 2 separated away from the mover. The piezoelectric stack 2 vibrated horizontally, and it deformed from $\alpha A$ to 0 along the right direction. At this stage, the mover was driven to the right.

The third stage ($1/2T$–$3/4T$): The piezoelectric stack 1 vibrated longitudinally, and it deformed from $\alpha A$ to 0. The piezoelectric stack 3 vibrated longitudinally, and it deformed from $\alpha A$ to $2\alpha A$. Therefore, the driving foot 1 separated away from the mover, while the driving foot 2 contacted the mover. The piezoelectric stack 4 vibrated horizontally, and it deformed from $2\alpha A$ to $\alpha A$ along the right direction. At this stage, the mover was still driven to the right.

The fourth stage ($3/4T$–$T$): The piezoelectric stack 1 vibrated longitudinally, and it deformed from 0 to $\alpha A$. The piezoelectric stack 3 vibrated longitudinally, and it deformed from $2\alpha A$ to $\alpha A$. Therefore, the driving foot 1 separated away from the mover, while the driving foot 2 contacted the mover. The piezoelectric stack 4 vibrated horizontally, and it deformed from $\alpha A$ to 0 along the right direction. At this stage, the mover was driven to the right.

And so far, the mover was driven to realize one period of linear motion by the two driving feet, and the mover would be driven to the left when we reverse the phase difference between the piezoelectric stacks 2 and 4.

Figure 2. The excitation signal.
Design of the nano-positioning stage

The nano-positioning stage has 3-DOF which were established by the serial structure. The stage could realize the linear motion along the $X$-axis and the $Y$-axis and the rotation motion around the $Z$-axis. The 3-DOF nano-positioning stage was shown in Figure 4.

It could be seen that the movement of each axis could be realized using the non-resonant piezoelectric linear actuator directly. Consequently, the complicated transmission mechanism and the conversion mechanism were both removed, and the inherent accumulation error in traditional serial structure could be eliminated. Obviously, the 3-DOF nano-positioning stage could meet the requirements of high accuracy and large working space synchronously.

Design of the translation platform

The structure diagram of the translation stage was shown in Figure 5. The high accuracy linear guide 5 was taken as the mover, which was driven directly by the two driving feet of the non-resonant piezoelectric linear actuator 2. To improve the driving effect and make the piezoelectric linear actuator run smoothly, a ceramic plate 3 with high hardness was used to paste on the front end of the friction pad 4,
Figure 4. The 3-DOF nano-positioning stage.
(1) Non-resonant piezoelectric linear actuator; (2) baseboard; (3) X-axis translational stage; (4) Y-axis translational stage; and (5) Z-axis rotation stage.

Figure 5. Structure of linear motion platform.
(1) Baseboard; (2) non-resonant piezoelectric actuator; (3) ceramic plate; (4) friction pad; and (5) THK linear guide.
which was also pasted on the front end of the THK linear guide 5. The piezoelectric linear actuator 2 was assembled onto the baseboard 1 by pins after the two driving feet contacted the ceramic plate 3 well, and the pre-tightening force between the two driving feet (stator) and the linear guide (mover) could be adjusted by the pre-tightening bolts.

The 2-DOF translation movement along the $X$-axis and the $Y$-axis could be realized by placing the two translation platforms orthogonally, one is on the top of the other, and the upper platform should be fixed with the top surface of the lower platform.

**Design of the rotation platform**

The structure diagram of the rotation platform was shown in Figure 6. The rotation component 3 was taken as the mover, which was driven directly by the two driving feet of the non-resonant piezoelectric linear actuator 2. The rotation assembly 3 was composed of the rotation platform 31, the bear 32, and the rotation shaft 33. The pre-tightening force between the two driving feet (stator) and the rotation component (mover) should also be able to be adjusted by the pre-tightening bolts when assembling the rotation platform. The rotation around the $Z$-axis could be realized by fixing the rotation platform with the top surface of the translation platform.

**Experiment**

**Experiment system**

The experiment system consisted of vibration isolation platform, signal generator, power amplifier, laser displacement sensor, and oscilloscope. The experiment
system was shown in Figure 7. The specification and type of the main experiment devices were selected as follows:

- Air floatation vibration isolation platform, ZDT10-08;
- Signal generator, MHS-2300A;
- Power amplifier, XE500-A4;
- Oscilloscope, Tektronix DPO2014;
- Laser displacement sensor, KEYENCE LK-HD500.

**Experiment of the piezoelectric actuator**

**Step motion mode.** First, it is necessary to verify the output performance of the piezoelectric actuator. In practical applications, the resolution of non-resonant piezoelectric linear actuator is defined as that the piezoelectric linear actuator could output the stable minimum step size under the minimum excitation voltage.

Under the no-load situation, and when the excitation signal was selected as the sine wave, its peak-to-peak value was 10 V and its frequency was 10 Hz, the preload was set as 40 N. Figure 8 shows the resolution of the piezoelectric actuator under the step motion mode as 0.015 μm.

**Continuous motion mode.** The purpose of the continuous motion of non-resonant piezoelectric linear actuator is to obtain the fast motion speed and large working
stroke. Under the same experiment condition, the output motion speed of the actuator increased gradually with the increase of the peak-to-peak value and its frequency of the excitation signal. Figure 9 shows the actuator’s motion speed of the continuous motion mode.

The excitation signal was still selected as the sine wave, the peak-to-peak value of the excitation signal was from 40 to 100 V, and the frequency was from 20 to 100 Hz. It could be found that if the peak-to-peak value of the excitation voltage and its frequency were higher, then the motion speed curve had better linearity. With the increase of the peak-to-peak value of the excitation voltage, the motion speed was increasing gradually. When the excitation voltage was fixed, the motion speed also increased slowly and linearly with the increase of the frequency of the excitation voltage.

Obviously, when the peak-to-peak value of the excitation voltage was 100 V, and its frequency was 100 Hz, the motion speed curve had the best linearity. The highest motion speed was 17.4 mm/s, which was greatly helpful to generate the fast motion and obtain the large working stroke.

**Experiment of the nano-positioning stage**

**Step motion mode.** The step motion mode is responsible for the micro-positioning with high resolution. Each DOF’s step resolutions of the step driving mode were shown in Figure 10.

---

*Figure 8. Actuator’s step resolution of the step motion mode.*
When the excitation signal was selected as the sine wave, and its peak-to-peak value was 10 V and its frequency was 10 Hz, the step resolution of the translation along the \( X \)-axis was \(0.018 \, \text{mm} \), the step resolution of the translation along the \( Y \)-axis was \(0.016 \, \text{mm} \) under the same experiment parameters, and the step resolution of the rotation around the \( Z \)-axis was \(0.3 \, \text{rad} \).

**Continuous motion mode.** It could be seen that when the peak-to-peak value of the excitation voltage was 100 V, and its frequency was 100 Hz, the actuator had the stable maximum motion speed (17.4 mm/s). Therefore, the continuous motion experiment of the nano-positioning stage could be carried out under the condition that is the same with that of the stable maximum motion speed. The experiment data shows that each DOF’s stable maximum motion speed of the nano-positioning stage is 12.88 mm/s, 14.09 mm/s, and 0.46 rad/s. Table 1 shows the key performance of each DOF of the nano-positioning stage.

![Figure 9. Actuator’s motion speed of the continuous motion mode.](image)

| Resolution  | Motion speed      | Working stroke |
|-------------|-------------------|----------------|
| Translation of \( X \)-axis | \(0.018 \, \mu \text{m} \) | 12.88 mm/s | 100 mm |
| Translation of \( Y \)-axis | \(0.016 \, \mu \text{m} \) | 14.09 mm/s | 100 mm |
| Rotation of \( Z \)-axis | \(0.3 \, \mu \text{rad} \) | 0.46 rad/s | 6.28° |

Lu and Chen

---

Table 1. The key performance of the nano-positioning stage.
Conclusion

1. The novel non-resonant piezoelectric linear actuator with the two motion feet based on the v-shaped stator was proposed. There were four piezoelectric stacks to compose the double driving feet (stator) and the two stators could drive alternately by the four sine waves that differed 90° in phase with each other.

2. The experiment results show that the resolution of the piezoelectric actuator is 0.015 μm, and its stable maximum motion speed is 17.4 mm/s, which was greatly helpful to generate the fast motion and obtain the large working stroke.

3. The piezoelectric linear actuator was applied into the 3-DOF precision nano-positioning stage, which was driven by the non-resonant piezoelectric linear actuator directly. The experiment results show that the nano-positioning platform has excellent ability of nano-resolution and large working range.

Figure 10. Each DOF’s step resolution of the step driving mode: (a) resolution of the X-axis; (b) resolution of the Y-axis; and (c) resolution of the Z-axis.
Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by National Natural Science Foundation of China (51805465 and 51405420), The Natural Science Foundation of the Jiangsu Higher Education Institutions of China (18KJB460030).

ORCID iD
Qian Lu https://orcid.org/0000-0002-9199-9352

References
1. Velasco HG. Parallel micromanipulator system with applications in micro assembles and micromachine-making. WSEAS Trans Sys 2005; 4(7): 980–987.
2. Dechev N, Ren L and Liu W. Development of a 6 degree of freedom robotic micro manipulator for use in 3D MEMS microassembly. In: Proceedings 2006 IEEE international conference on robotics and automation, 2006. ICRA 2006, Orlando, FL, 15–19 May 2006, pp. 281–288. New York: IEEE.
3. Wang ZH, Chen LG and Sun LN. An integrated parallel micromanipulator with flexure hinges for optical fiber alignment. In: 2007 international conference on mechatronics and automation, Harbin, China, 5–8 August 2007, pp. 2530–2534. New York: IEEE.
4. Ouyang PR, Zhang WJ and Gupta MM. Overview of the development of a visual based automated bio-micromanipulation system. Mechatronics 2007; 17(10): 578–588.
5. Li YM, Tang H and Xu QS. The development status of micromanipulator technology for biomedical applications. Chin J Mech Eng 2011; 47(23): 1–13.
6. Srivatsan RA. On the position kinematic analysis of MaPaMan: a reconfigurable three degrees-of-freedom spatial parallel manipulator. Mech Mach Theory 2013; 62: 150–165.
7. Umesh B, Shirinzadeh B and Clark L. Design and analysis of a novel flexure based 3-DOF mechanism. Mech Mach Theory 2014; 74(4): 173–187.
8. Do TN, Tjahjowidodo T and Lau MWS. Hysteresis modeling and position control of tendon-sheath mechanism in flexible endoscopic systems. Mechatronics 2014; 24(1): 12–22.
9. Meng QL, Li YM and Xu J. A novel analytical model for flexure-based proportion compliant mechanisms. Precis Eng 2014; 38(3): 449–457.
10. Gallardo AJ, Rodriguez CR and Aguilar NCR. A novel six-degrees-of-freedom series-parallel manipulator. J Mech Sci Tech 2012; 26(6): 1901–1909.
11. Sun LN and Dong W. Stiffness analysis on a wide-range flexure hinge-based parallel manipulator. Chin J Mech Eng 2005; 41(8): 90–95.
12. Yun Y and Li YM. Design and analysis of a novel 6-DOF redundant actuated parallel robot with compliant hinges for high precision positioning. Nonlinear Dyn 2010; 61(4): 829–845.
13. Xu QS. Design and testing of a novel multi-stroke micropositioning system with variable resolutions. *Rev Sci Instrum* 2014; 85(2): 025002.

14. Shayya S and Krut S Company O. A novel (3T-2R) parallel mechanism with large operational workspace and rotational capability. In: *2014 IEEE international conference on robotics and automation (ICRA)*, Hong Kong, China, 31 May–7 June 2014, pp. 5712–5719. New York: IEEE.

15. Shan MC, Ma SY and Xie H. Vertical axis precision positioning system based on ultrasonic linear motor. *Micromotors* 2013; 46(10): 41–43.

16. Olfatnia M, Cui LQ and Chopra P. Large range dual-axis micro-stage driven by electrostatic comb-drive actuators. *J Micromech Microeng* 2013; 23(10): 5008–5018.

17. Kurosawa MK and Kodaira O. Transducer for high speed and large thrust ultrasonic linear motor using two sandwich-type vibrators. *IEEE T Ultrason Ferr* 1998; 45(5): 1188–1195.

18. Chen PH, Wang Y and Huang WQ. The design of a new direct action piezoelectric linear motor. *Piezoelect Acoust* 2011; 33(2): 239–243.

**Author biographies**

Qian Lu, received his Ph.D. from Nanjing University of Aeronautics and Astronautics in 2018. Now he is an associate professor of Yancheng Institute of technology. His main research interests are piezoelectric driving technology, piezoelectric actuation testing technology and instruments.

Xifu Chen, received his Ph.D. from Nanjing University of Aeronautics and Astronautics in 2014. Now he is an associate professor of Yancheng Institute of technology. His main research interests are the design and application of new piezoelectric motor.