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Design and experimental research of a novel inchworm type piezo-driven rotary actuator with the changeable clamping radius

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In this paper, a novel piezo-driven rotary actuator with the changeable clamping radius is developed based on the inchworm principle. This actuator mainly utilizes three piezoelectric actuators, a flexible gripper, a clamping block, and a rotor to achieve large stroke rotation with high resolution. The design process of the flexible gripper consisting of the driving unit and the clamping unit is described. Lever-type mechanisms were used to amplify the micro clamping displacements. The amplifying factor and parasitic displacement of the lever-type mechanism in the clamping unit was analyzed theoretically and experimentally. In order to investigate the rotation characteristics of the actuator, a series of experiments was carried out. Experimental results indicate that the actuator can rotate at a speed of 77 488 \( \mu \text{rad/s} \) with a driving frequency of 167 Hz. The rotation resolution and maximum load torque of the actuator are 0.25 \( \mu \text{rad} \) and 37 N mm, respectively. The gripper is movable along the \( z \) direction based on an elevating platform, and the clamping radius can change from 10.6 mm to 25 mm. Experimental results confirm that the actuator can achieve different rotation speeds by changing the clamping radius. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4788736]

I. INTRODUCTION

Piezoelectric (PZT) material is a type of smart material with quick response, large output force, and high displacement resolution and so on. Lots of the high-precision positioners integrating PZT actuators have been developed by researchers.1–5 The stroke of the PZT actuator is usually limited to several micrometers or several tens of micrometers. To obtain a large motion stroke while maintaining a satisfactory resolution of displacement, some novel actuation methods or principles have been developed, which can be mainly classified into inertial drive type,6–8 and inchworm type.9–11

Many PZT actuators have been developed based on the inertial drive principle, such as the linear walking actuator12 and the precision sliding stage.13 This type of device usually has the drawback of the small driving force due to friction as a part of its working process.

The inchworm actuator is a kind of bionic actuator with the advantages of high loading capacity, large travel range, and good controllability. S. Yan et al. developed a stepping actuator with three degrees of freedom, which can achieve large stroke translation and rotation with high resolution on a platform.14 A compact high precision stepping positioner for the precision alignment of optical elements was designed by D. Kang et al.15 The main disadvantage of this type is that complex flexure hinge structure is frequently used.

Researches on piezo-driven actuators with inchworm motion in rotational direction are rare.16–19 These actuators usually have difficulties in assembly because of a strict gap requirement between the stator and the rotor. Some of them have an angular step size larger than 1 \( \mu \text{rad} \), the maximum loading torque less than 10 N mm and the maximum driving frequency lower than 100 Hz. These characteristics restrict their application in ultra-precision positioning. Besides, the rotation speed of these actuators can only be adjusted by the amplitude or frequency of the applied voltage.

In this paper, a novel inchworm type piezo-driven actuator is presented, which can perform large stroke rotation with high resolution. The clamping radius of the actuator is changeable. As a result, the rotary actuator can realize a new speed adjustment mode named variable clamping radius besides variable voltage and variable frequency. The actuator has a large range of rotation speed and the speed can be controlled easily.

II. CONFIGURATION AND THE OPERATING PRINCIPLE

Fig. 1 shows the model of the rotary actuator, which mainly consists of a flexible gripper, a clamping block, a manual translation stage, an elevating platform, a rotor, a base, and three PZT actuators. The flexible gripper and the clamping block are composed of flexure hinges and can be fabricated by wire-cutting. As a key element of the actuator, the flexible gripper is used to clamp and drive the rotor. The gripper can be divided into two parts, which are called the clamping unit and the driving unit in this paper, as shown by the dotted lines in Fig. 1. The PZT actuators A and B are installed in the clamping unit and the driving unit, respectively. Integrating the PZT actuator C, the clamping block is used to hold the
rotor and ensure the rotor will not move under external forces or moments. The rotor is supported by a pair of ball bearings. The manual translation stage is used to adjust the gripper along the $x$ direction, which can increase assembly precision and reduce assembly difficulties between the flexible gripper and the rotor. Besides, the gripper is also movable along the $z$ direction via the elevating platform and the clamping radius is changeable. The stepping rotation is achieved by the sequential deformations and contractions of the flexure hinges, which can be controlled by the applied voltages on the PZT actuators.

Fig. 2 shows the input voltages applied on the three PZT actuators. The driving process is shown in Fig. 3. According to Figs. 2 and 3, one complete rotation cycle can be divided into steps (1)–(6). Initially, the PZT actuators are all with their natural lengths and no voltages are applied on them. There are small initial gaps between surfaces of the rotor and clamping surfaces of the clamping mechanisms. The detailed driving process is as follows:

1. In the first phase, the PZT actuator A extends with a voltage applied on it. Deformation of the PZT actuator A is amplified through the amplifying mechanism of the clamping unit. The amplified deformation is larger than the initial gap between surfaces of the rotor and clamping surfaces of the clamping unit, and the rotor is clamped by the clamping unit.

2. In the second phase, the PZT actuator B extends over a micro length $d$, and the rotor rotates through a micro angle $\theta$. The micro rotation angle is given as

$$\theta = \frac{d}{R}, \quad (1)$$

![FIG. 1. Model of the rotary actuator.](image1)

![FIG. 2. Synchronized input voltages on the PZT actuators.](image2)

![FIG. 3. Driving process of the proposed inchworm type actuator. (a) The rotor is clamped by the clamping unit. (b) The driving unit outputs a linear displacement and the rotor rotates through a micro angle. (c) The rotor is clamped by the clamping unit and the clamping block at the same time. (d) The clamping unit recovers to its initial state. (e) The driving unit returns to its initial position. (f) The rotor is clamped by the clamping unit and the clamping block again.](image3)
III. DESIGN AND ANALYSIS

A. The flexible gripper

Comparing to conventional mechanisms with sliding and rolling bearings, the flexure hinge takes advantages of simple and compact structure, no lubrication, and high positioning accuracy. For those reasons, the flexure hinge has been widely used in the fields of micro-gripper, micro-positioning, micromanipulation, and so on.

A novel flexible gripper integrating the clamping and driving functions was designed and the model is shown in Fig. 4. The gripper has a symmetric structure and mainly consists of some right-circular flexure hinges and right-angle flexure hinges.

Due to the machining and assembling errors, a large and irregular gap may appear between the clamping unit and the rotor. In order to ensure that the rotor can be clamped stably by the clamping unit, a lever-type amplifying mechanism is utilized to enhance the clamping displacement produced by the PZT actuator A. Another similar structure is adopted in the clamping block. Considering the symmetry of the lever-type amplifier, only half of the structure is analyzed here. Geometric model of the lever-type mechanism is shown in Fig. 5. It is assumed that the right-circular flexure hinge is the pivot and the mechanism rotates around it. \( l_A \) is the length from the input end to the pivot and \( l_B \) is the length from the output end to the pivot. \( x_A \) is the input displacement of the input end and \( x_B \) is the output displacement of the output end.

The amplifying factor of the lever-type mechanism can be calculated as follows:

\[
\lambda = \frac{x_B}{x_A} = \frac{l_B}{l_A} \cdot \frac{\sin(\phi + \Delta\phi) - \sin\phi}{\sin \Delta\phi \cdot \cos \phi} = \frac{l_B}{l_A} \cdot \frac{\sin \Delta\phi + \tan \phi \cdot (\cos \Delta\phi - 1)}{\sin \Delta\phi} = \frac{l_B}{l_A} \left(1 - \tan \phi \cdot \tan \frac{\Delta\phi}{2}\right),
\]

where \( \phi \) has a constant value of about 21°, \( \Delta\phi \) is the rotation angle of the lever-type structure with a input displacement of \( x_A \). Considering the rotation angle \( \Delta\phi \) is very small (\( \ll 1\degree \)), Eq. (2) can be simplified as

\[
\lambda = \frac{l_B}{l_A}. \tag{3}
\]

Here, \( l_A \) is 6.8 mm and \( l_B \) is 27.5 mm. And the theoretical amplifying factor of the lever-type mechanism is about 4.044.

A large output displacement along the x direction can be acquired at the output end through the amplifying mechanism. Meanwhile, a displacement along the y direction will appear on the output end of the clamping unit, which is called the parasitic displacement in this paper. Similarly, the parasitic displacement \( y_B \) can be calculated as follows:

\[
y_B = x_B \cdot \tan \phi. \tag{4}
\]

The parasitic displacement has a negative effect on precise control of the proposed inchworm-type actuator. During the driving step (4) and (6) (shown in Fig. 3), the rotor may rotate through a parasitic angle due to the parasitic displacement of the clamping unit. In order to avoid the parasitic rotation, the clamping block should provide a large and stable clamping force to keep the rotor fixed. However, this parasitic displacement can also be used to drive the rotor with a sawtooth wave applied on the PZT actuator A.\(^{20}\)

The amplifying factor and the parasitic displacement of the amplifying mechanism were tested by experiments. The
applied voltage on the PZT actuator A was a rectangle wave with a voltage step of 5 V and peak amplitude of 100 V. The input displacement, the output displacement and the parasitic displacement of the clamping unit are shown in Fig. 6.

In Fig. 6, all of these three displacements, $x_A$, $x_B$, and $y_B$, increase with the increase of the applied voltage. The output displacement $x_B$ is obviously larger than the input displacement $x_A$. The maximum input displacement and output displacements are about 12.23 μm and 41.39 μm, respectively. Experimental results indicate that the actual amplifying factor is 3.384, which is smaller than the theoretical value with a relative error of 16.32%. During the theoretical analysis of the amplifying factor, the right-circular flexure hinge is regarded as a rigid pivot and its elastic deformation is out of consideration. Actually, the flexure hinge will generate an elastic deformation along the x direction during the amplification process and the rotation pivot of the lever-type structure will move along the x direction. Compared with the theoretical input displacement, the effective input displacement is smaller. As a result, the effective output displacement will be smaller than the theoretical output displacement. With the maximum output displacement is 41.39 μm, the maximum parasitic displacement is about 15.89 μm according to Eq. (4). The experimental maximum parasitic displacement is about 16.44 μm, which agrees well with the theoretical value of 15.89 μm.

B. The elevating platform

Fig. 7 shows the main parts of the elevating platform. Wedge A and wedge B contact with each other and can move along the linear guides on plate A and plate B, respectively. A micrometer head with a stroke of 13 mm and a resolution of 1 μm is used to provide the driving force for wedge B.

The platform works as follows:

Twist the micrometer head and the wedge B is pushed to move forward along the linear guide on plate B for a distance $\Delta y$, and the wedge A moves upward along the linear guide on plate A for a distance $\Delta z$. Stop twisting the micrometer head when the expected radius is acquired. The radius will be fixed with the self-locking characteristics of the micrometer head.

The relationship between $\Delta y$ and $\Delta z$ is given as

$$\Delta z = \Delta y \cdot \tan \alpha,$$

where $\alpha$ is the angle between the inclined plane and the horizontal plane and the value is 55°.

The gripper can move along the z direction based on this elevating platform and the clamping radius ranges from 10.6 mm to 25 mm. However, an eccentricity may appear between the actual clamping surface center and the theoretical clamping surface center. And the actual clamping radius will be different from the theoretical clamping radius with a deviation. The deviation of the clamping radius is less than 3 mm, which is the half thickness of the gripper.

IV. EXPERIMENTS

In this section, a series of experiments were carried out to evaluate the characteristics of the proposed rotary actuator.

A. Experiment system

Three PZT actuators AE0505D16 from Tokin Company are used in this actuator. Fig. 8 is the established experiment system, and the working flow of the experiment system is showed in Fig. 9. A programmable multi-axis controller (PMAC) is used to generate the original voltage signals. The frequencies and amplitudes of the voltage signals can be controlled by the personal computer (PC) through a parallel
interface. The PMAC is supplied by a direct current (DC) regulated power supply. The original voltage signals are amplified by the piezo controllers from PI Company and then are applied on the three PZT actuators. The displacement of the rotary actuator is measured by a laser displacement sensor LK-G10 from Keyence Company with the resolution of 10 nm. The displacement signal is converted by an analog to digital (A/D) card and stored in the PC. Fig. 10 is a photograph of the rotary actuator prototype. Some thin copper sheets are used to provide the preloads for the PZT actuators.

### B. Stepping rotation characteristics

The rotation speed of the inchworm actuator depends on both the step size and the driving frequency, which can be expressed as follows:

$$\omega = \theta \cdot f = \frac{d \cdot f}{R}, \quad (6)$$

where $\omega$ is the rotation speed, $f$ is the driving frequency.

Considering the displacement of PZT actuator is proportional to the driving voltage (peak to peak value), Eq. (6) can change to

$$\omega \propto \frac{U \cdot f}{R}, \quad (7)$$

where $U$ is the driving voltage.

In previous rotary inchworm actuators, the clamping radiiuses are constant and their rotation speeds can only be adjusted by the driving voltage and the driving frequency. However, the clamping radius of the actuator is changeable based on the elevating platform. The rotation speed can be controlled by the driving voltage, the driving frequency and the clamping radius at the same time.

#### 1. Driving voltage

Fig. 11 shows the stepping rotation displacements under eight different driving voltages when the frequency is 1 Hz and the clamping radius is 21 mm. The step size increases with the increase of driving voltage, and the maximum step size is about 378 $\mu$rad. Therefore, the rotation angle per step of this actuator can be controlled by choosing a proper driving voltage. For the actuator, the rotation resolution is the minimum stable step size. The rotation resolution testing result is shown in Fig. 12. An accumulated rotation displacement of about 5 $\mu$rad is obtained after the actuator rotates for 20 steps. In
this test, the driving voltage is 8 V, and the actuator cannot rotate stably when the driving voltage is lower than that value. According to these results, it can be concluded that the actuator can rotate stably under various driving voltages (no lower than 8 V) with a resolution of 0.25 μrad. The rotation displacement is fluctuant with the amplitude of about 25 μrad. The fluctuation is mainly caused by the bearing clearance, and the clearance can be reduced by adopting more precise bearing system. Besides, the tolerance clearance between the rotor shaft and the ball bearings also has an effect on the fluctuation. The tolerance clearance can be avoided by selecting a proper transition fit or interference fit between them.

2. Driving frequency

According to Eq. (1), the rotation angle per step of the actuator only depends on the output displacement of the PZT actuator B and the clamping radius. However, the theoretical model is just an ideal model and some possible influencing factors are not considered. In some certain circumstances, the driving frequency will also affect the step size of the actuator. The relationship between the stepping rotation displacement and the clamping radius is shown in Fig. 14, while the driving frequency is 1 Hz and the driving voltage changes from 100 V to 70 V. The rotation displacement decreases gradually when the clamping radius changes from 23 mm to 14 mm under each driving voltage. The largest step size is about 548 μrad with a driving voltage of 100 V and a clamping radius of 14 mm while the smallest step size is about 186 μrad with a driving voltage of 70 V and a clamping radius of 23 mm.

3. Clamping radius

The clamping radius of the actuator is changeable, and it can be an effective parameter to control the rotation angle per step and the rotation speed of the actuator. The relationship between the stepping rotation displacement and the clamping radius is shown in Fig. 13, while the driving frequency is 1 Hz and the driving voltage changes from 100 V to 70 V. The rotation displacement decreases gradually when the clamping radius changes from 23 mm to 14 mm under each driving voltage. The largest step size is about 548 μrad with a driving voltage of 100 V and a clamping radius of 14 mm while the smallest step size is about 186 μrad with a driving voltage of 70 V and a clamping radius of 23 mm.

C. Rotation speed characteristics

With a frequency of 1 Hz, the relationship between the rotation speed and the driving voltage is shown in Fig. 15(a). The rotation speed of the rotary actuator increases with the increase of the driving voltage. A rotation speed of about 378 μrad/s is obtained when the driving voltage, the driving frequency and the clamping radius are 100 V, 1 Hz, and 21 mm, respectively. The relationship between the rotation speed and the driving frequency with a driving voltage of 100 V and a clamping radius of 21 mm is illustrated in Fig. 15(b). The rotation speed changes from 378 μrad/s to 77 488 μrad/s when the frequency increases from 1 Hz to 167 Hz.

The relationship between the rotation speed and the clamping radius is shown in Fig. 15(c). The rotation speed decreases from 548 μrad/s to 334 μrad/s while the clamping radius changes from 14 mm to 23 mm with a driving voltage of 100 V and a driving frequency of 1 Hz. It has been theoretically deduced that inversely linear dependency exists between the rotation speed and the clamping radius. However, such a relationship is not found through the experimental results shown in Fig. 15(c). It is mainly caused by the eccentricity between the actual clamping surface center of the clamping unit and the theoretical clamping surface center. Therefore, the actual clamping radius may be larger or smaller than the theoretical radius.
FIG. 14. Rotation displacements under different clamping radiiuses with a driving frequency of 1 Hz.

D. Loading capacity

Loading capacity is a key performance parameter because it influences the application of the actuator. Through the analysis of the driving process, the loading capacity of the proposed actuator is determined by the driving mechanism and the clamping mechanisms. It is assumed that the rotor can be fixed by the clamping unit or the clamping block under various external loads. The rotor rotates under the driving force produced by the PZT actuator B, and the rotation angle per

FIG. 15. Rotation speed versus (a) the driving voltage, (b) the driving frequency, and (c) the clamping radius.
step depends on the output displacement of the driving unit. Many factors have effects on the output displacement of the driving unit, including the driving voltage, the piezoelectric material characteristics, and the external load and so on. In this paper, the effect of the external load on output displacement is mainly analyzed. The mechanical model of the driving unit under load condition is established, as shown in Fig. 16.

The mechanical model consists of the PZT actuator B, an external load \( F_l \), and two springs with a stiffness coefficient of \( K_s \). The springs are the simplified models of the symmetric right-angle flexure hinges. For the PZT actuator B, \( L_0 \) is the natural length, \( \Delta L_0 \) is the output displacement under no-load condition with a driving voltage of \( U \), and \( \Delta L \) is the output displacement under load condition with the same driving voltage. The force equilibrium equation of the model can be expressed as follows:

\[
K_p \cdot (\Delta L_0 - \Delta L) = K_s \cdot \Delta L + F_l, \tag{8}
\]

where \( K_p \) is the stiffness coefficient of the PZT actuator B.

The relationship between the output displacement and the external load can be expressed as follows:

\[
\Delta L = \frac{K_p \Delta L_0 - F_l}{K_p + K_s}. \tag{9}
\]

The output displacement of the PZT actuator B under load condition will decrease with the increase of external load. According to Eq. (1), the rotation angle per step of the actuator under load condition will decrease as well.

A loading capacity testing system was established to analyze the effect of external load on the rotation displacement, as shown in Fig. 17(a). The load torque applied on the rotor was generated through a weight connected to the rotating shaft of rotor with the arm of force of 15 mm, as shown in Fig. 17(b). These tests were carried out when the frequency, the driving voltage and the clamping radius were 1 Hz, 100 V, and 21 mm, respectively.

Fig. 18 shows the rotation angle per step of the actuator under different external loads. With the weight increases from 0 to 250 g, the rotation angle per step decreases from 378 \( \mu \)rad to 19 \( \mu \)rad, which is consistent with the theoretical analysis. When the weight is more than 250 g, the actuator cannot rotate stably in the direction presented in Fig. 17(b). Therefore, the maximum load torque of the actuator is about 37 N mm.

V. CONCLUSIONS

A novel inchworm-type rotary actuator with the changeable clamping radius was proposed. This actuator can achieve three types of speed adjustment modes, named variable voltage, variable frequency, and variable clamping radius. The clamping radius can range from 10.6 mm to 25 mm based on an elevating platform. The stepping characteristics and the rotation speed characteristics of the rotary actuator were tested by a series of experiments. For the rotary actuator, the largest rotation speed is 77 488 \( \mu \)rad/s, the maximum load torque is 37 N mm, and the resolution is 0.25 \( \mu \)rad. With a clamping radius of 21 mm and a driving frequency of 1 Hz, a rotation speed of 378 \( \mu \)rad/s is obtained while the driving voltage is 100 V. The rotation speed decreases from 548 \( \mu \)rad/s to 334 \( \mu \)rad/s while the clamping radius increases from 14 mm to 23 mm with a driving voltage of 100 V and a frequency of 1 Hz. However, the rotation speed does not decrease linearly with the clamping radius while the driving voltage and the driving frequency are all constant. This result is mainly caused by the deviation between the actual clamping radius and the theoretical clamping radius. The deviation has a negative effect on the precise control of the rotation speed through adjusting the clamping radius. Improvements will be carried out in the future to reduce or eliminate the deviation.

In summary, preliminary experiments verify the feasibility of the proposed actuator. Next step, more experiments will be carried out to test other output performances of the actuator, such as the maximum or the minimum driving frequency, the rotation repeatability and so on. In this paper, only the
effects of the output displacement and the driving force of the PZT actuator B on the loading capacity of the actuator are analyzed. Actually, the loading capacity also depends on some other factors, including the clamping forces of the PZT actuators A and C, the driving frequency, et al. More research will be focused on analyzing these influencing factors.

Lever-type mechanisms are utilized in the proposed actuator to amplify the clamping displacements. The amplifying factor of the lever-type mechanism in the clamping unit was analyzed theoretically and experimentally. In order to simplify the geometric model of the lever-type mechanism, the elastic deformation of the flexure hinge is out of consideration. It is been found that a large relative error exists between the theoretical amplifying factor and the experimental amplifying factor. A more precise model including the elastic deformation of the flexure hinge will be established in the future. Besides, a parasitic displacement will appear on the output end of the lever-type mechanism, which can also be used to drive the rotor. The feasibility of the parasitic rotation will be researched by experiments in the future.

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