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Chapter

Principle, Design and Future of Inchworm Type Piezoelectric Actuators

Jianping Li, Jianming Wen, Yili Hu, Zhonghua Zhang, Lidong He and Nen Wan

Abstract

The inchworm type piezoelectric actuator is one novel actuator to ensure a large working stroke with high resolution which has attracted the continuous attentions from researchers all over the world. In this study, the motion principle of the inchworm type piezoelectric is discussed: the "walker" pattern, the "pusher" pattern and hybrid "walker-pusher" pattern. The classification (linear, rotary and multi-DOF) and development are introduced in details, some significant researches are illustrated. Finally, the future direction of inchworm type piezoelectric actuators is pointed out according the development of inchworm type piezoelectric actuators. This study shows the clear principle, design and future of inchworm type piezoelectric actuators which is meaningful for the development of piezoelectric actuators.

Keywords: piezoelectric actuator, inchworm, large stroke, high resolution

1. Introduction

Up to now, researchers have developed a variety of micro/Nano driving and positioning platforms based on piezoelectric materials. Among the developed piezoelectric platforms, many of them have been applied for biological cell manipulation, atomic manipulation, micro/nano indentation, aerial photography and other systems with great application results [1, 2]. However, the working stroke of piezoelectric components is quite small, often only a few micrometers or tens of micrometers, which seriously limits the further application of piezoelectric actuators. Therefore, many researchers have done a lot of work to overcome this shortcoming of piezoelectric components, so as to expand the application field of piezoelectric actuators [3]. The inchworm type piezoelectric actuator is one kind of the developed new piezoelectric actuators which is able to ensure a large working stroke and achieve nano-scale accuracy at the same time. It has a wide application demand in the fields which have strict requirements on output accuracy, space size and antielectronmagnetic interference. The study on inchworm piezoelectric actuators has become a hot spot in the application and research field of piezoelectric actuators in recent years [4, 5].

2. Motion principle

The inchworm type piezoelectric actuator mimics the motion principle of the real inchworm in nature, as is illustrated in **Figure 1(a)** [6]. Sometimes, it is called one kind of novel bionic actuators. It is found that the natural inchworm moves smoothly by stepping motion form. With the help of the stepping motion form and the piezoelectric technology, large working stroke is easy to be achieved by inchworm actuators through the alternating motion of driving units and clamping units. At the same time, compared with other piezoelectric actuators, the use of clamping unit brings larger output force. The inchworm type piezoelectric actuator usually consists of one driving unit and two clamping units. According to the difference of motion modes, inchworm type piezoelectric actuators could be split into three motion patterns: the "walker" pattern, the "pusher" pattern and hybrid "walker-pusher" pattern.

Figure 1(b) shows the motion principle of the "walker" pattern piezoelectric actuator, which is essentially similar to the walking mode of the real inchworm in nature. The "walker" mechanism obtains a large working stroke by repeating the following six steps: (1) in the original position, all piezoelectric elements in the driving unit and clamping units do not work, so there is a gap between the clamping device and the base guider; (2) the piezoelectric element in clamping unit 1 obtains the power, and then clamping unit 1 holds the base guide tightly; (3) the driving unit is extending while the piezoelectric element inside it obtains the power; (4) the clamping unit 2 obtains the power to tightly fix the base guider and the clamping unit 1; (5) the clamping unit 1 loses power to release the base guider; (6) the driving unit returns to its original length. Finally, the clamping unit 2 is de energized to release the base guider in the same original position as in step (1). By repeating these six steps, a large working stroke is achieved gradually [7].

The "push" pattern piezoelectric actuator also needs six steps to obtain a step motion, as shown in **Figure 1(c)**: (1) in the original position, all of the driving and clamping units have no power to fix the slider; (2) the clamping unit 2 obtains the power to hold the slider tightly; (3) the driving unit gets power to push the clamping unit 2, and since the slider is hold by clamping unit 2 tightly, it will move forward for small moving distance; (4) the clamping unit 1 holds the slider; (5) the clamping unit 2 is powered off to release the slider; (6) the driving unit returns to the original length when it loses power. At last, the clamping unit 1 releases the slider to the same condition as in the original position [8].

Hybrid "Walker-pusher" pattern piezoelectric actuator is a hybrid of "Walker" and "pusher" modes. The difference is that the driving unit is inserted into the sliding block, and the clamping unit is assembled in the base in the "Walker-pusher" mode [9].

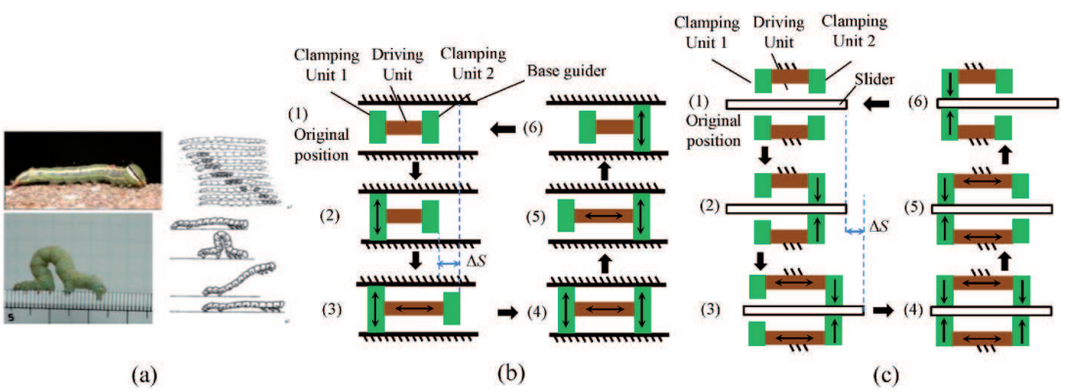


Figure 1.
Motion principles: (a) real inchworm; (b) "walker" pattern; (c) "pusher" pattern.

3. Classification and development

Inchworm type piezoelectric actuator has been widely concerned by researchers because it is able to ensure long working stroke, high precision and large output at the same time. Many inchworm driving devices have been developed. According to the different motion forms, they could be divided into the linear actuator, the rotary actuator and the multi-DOF actuator.

3.1 Linear inchworm actuator

As early as in 1964, Stibitz developed the first "pusher" inchworm actuator with magnetostrictive elements to generate driving force, so as to solve the positioning problem of machining tools [10]. Three magnetostrictive elements are utilized as driving and clamping units to generate large stroke linear stepping motion. However, limited by the technical conditions, its performance is not very high, but the driving principle of the inchworm movement provides a new space for the research of precision positioning technology. After that, Hsu et al. proposed the inchworm piezoelectric actuator for the first time [11]. As shown in **Figure 2(b)**, the piezoelectric element is applied to convert the electrical signal into mechanical motion, and two unidirectional clamps are combined to accumulate the movement of the electric element. A piezoelectric tube is inserted into the slider so that it is in the mixed "walker-pusher" mode. In 1968, Brisbane invented the first "walker" type inchworm piezoelectric actuator [12]. Two piezoelectric disks and one piezoelectric tube are assembled inside the slider, which makes it possible to realize the linear motion of the slider by walking which is illustrated in **Figure 2(c)**.

However, due to the immaturity of piezoelectric materials at that time, the development of inchworm type piezoelectric actuators was hindered. For many years, even though there were still some researches on inchworm type piezoelectric actuators, most of them only focused on the theoretical research. Until the end of the 1980s, commercial piezoelectric elements were able to provide an output force of up to several thousand newtons, and the driving voltage dropped from 1000 V to 200 V. All of these provided great opportunities for the further development of piezoelectric actuators. After that many researchers have focused on the development of inchworm type piezoelectric actuators. By using three packaged piezoelectric stacks forming a U-shaped structure, Chen et al. proposed a "pusher" pattern inchworm type piezoelectric actuator [13]. The experimental results show that the maximum driving force is 13.2 N and the maximum speed is 47.6 μm/s. With the help of adding an integrated heterodyne interferometer as feedback device in the servo control system, an inchworm type piezoelectric actuator with fast response is developed by Moon et al. [14]. Based on the fast response characteristics of the servo control system, it can move to the target position quickly and reduce the hysteresis of the piezoelectric actuator.

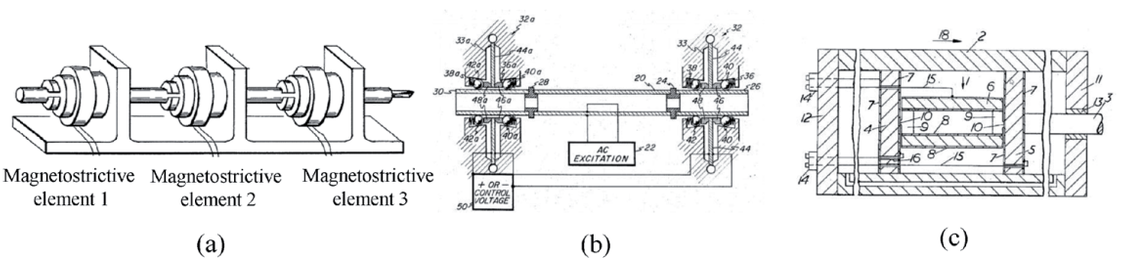


Figure 2.
Inchworm actuators: (a) the first inchworm actuator [10]; (b) the first inchworm type piezoelectric actuator [11]; (c) the first "walker" pattern inchworm piezoelectric actuator [12].

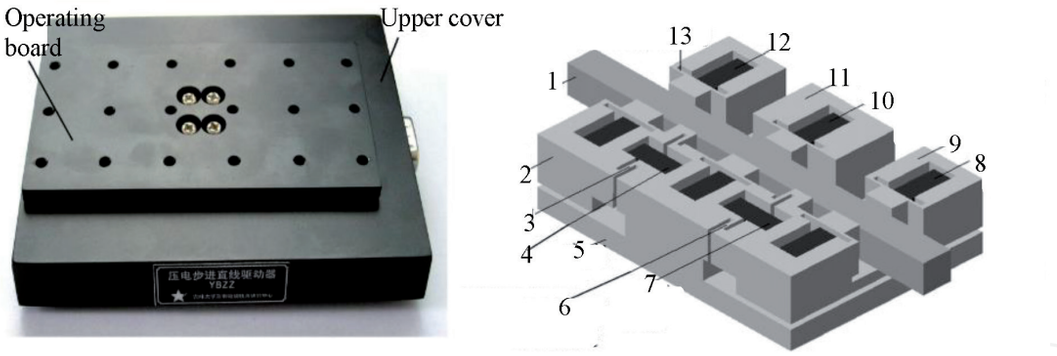


Figure 3.
Inchworm actuator developed by Yang et al. [17].

However, an important problem is that the extension length of piezoelectric elements is very small, which brings trouble to the clamping unit to clamp the slider tightly. Therefore, many literatures are focusing on different methods to improve the clamping unit. As a typical compliant mechanism, the flexure hinge mechanism has been widely applied in the design of piezoelectric actuators to expand the elongation of piezoelectric elements due to its advantages of fast response, no friction and easy manufacturing. In 1988, Fujimoto firstly proposed an inchworm type piezoelectric actuator with flexible hinge [15]. This "walker" type piezoelectric actuator adopts C-shaped lever type flexible hinge on both clamping units to increase the clamping force, and it has great practical value for the real application of inchworm piezoelectric actuators. The magnification could be adjusted by changing the position of the pivot point. Kim constructed an inchworm platform with an amplification stage, and it utilized the flexure hinge as a lever mechanism to obtain a magnification of 8.4 at a leverage ratio of 3.6 [16].

The research team of Jilin University and Zhejiang Normal University has carried out systematic research on the development of inchworm piezoelectric actuators. After years of experience, it has developed series of Inchworm piezoelectric actuators, and has achieved a series of remarkable research results. For example, Yang et al. proposed a novel linear piezoelectric actuator [17] (**Figure 3**). The proposed actuator adopts the principle of "pusher" motion pattern, and realizes the passive linear motion of the slider with the help of clamping and driving units. Based on the analysis of the working principle and the mechanical structure of the actuator, a linear driving mathematical model with the piezoelectric stack as the driving element is established, and its structure is analyzed by finite element method (FEM). The proposed inchworm piezoelectric actuator adopts the principle of bidirectional thrust, and realizes the consistency of driving characteristics in the process of forward and reverse directions. Experimental results show that the novel inchworm actuator has the characteristics of firm clamping, high frequency (100 Hz), high step speed (30 mm/min), large stroke (> 10 mm), high resolution (0.05 μm) and large driving force (100 N), which greatly improves the driving performance of the inchworm piezoelectric actuator. It has a broad further application in precision motion, micromanipulation, optical engineering, and precise positioning and so on.

3.2 Rotary inchworm actuator

Besides the inchworm piezoelectric actuators to achieve linear motion, some inchworm actuators which could obtain rotary motion have been developed by researchers. Kim et al. developed a new type of inchworm piezoelectric actuator that uses a combination of flexure hinge and piezoelectric drive technology to

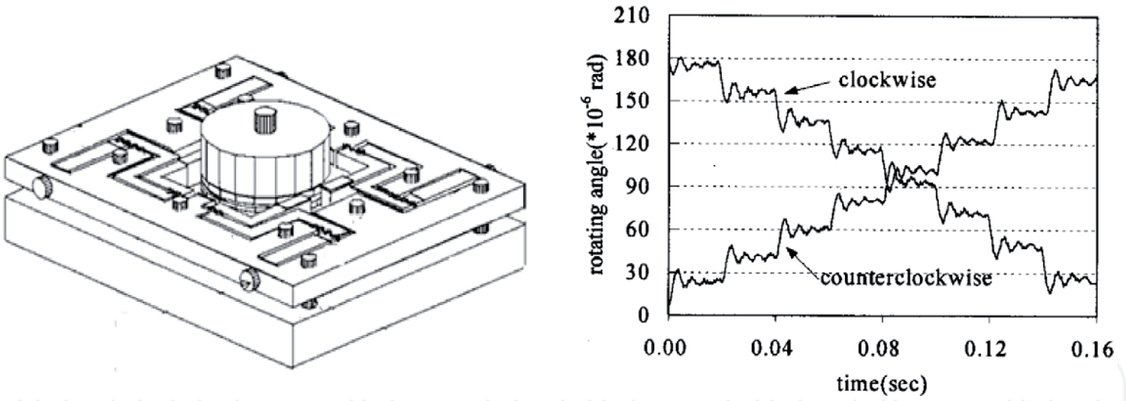


Figure 4.
Inchworm type piezoelectric actuators with flexible belts by Kim et al. [18].

achieve rotational movement [18] (**Figure 4**). The device pioneered the use of linear output piezoelectric stacks to achieve an inchworm-shaped rotary motion, which has extremely high research significance. The device realizes the movement of the flexible hinge by controlling the power-on sequence of the four piezoelectric stacks, thereby driving the belt wound on the rotating shaft to drive the rotating shaft to rotate. The test results show that the resolution of the rotary drive device can reach 2.36 μrad, which is greatly improved compared to the previous rotary drive device.

In view of the shortcomings of the existing inchworm actuators, Li et al. firstly designed an inchworm type piezoelectric actuator based on multi-layer torsional flexure hinges, which is able realize the rotary motion with large working stroke and high precision [4]. The developed actuator utilizes the piezoelectric stack to push the thin-walled flexure hinge structure to carry out relevant clamping. By controlling the working sequence of the clamping units in the first and second layers of the stator, the precise rotary motion around the fixed shaft is realized step by step. Its structure is divided into two main parts: rotor and stator. According to the function, it could be divided into the driving unit, the clamping unit and the preloading unit. The proposed device uses high-precision piezoelectric stack to push the thin-walled flexure hinge structure for relevant clamping. By controlling the clamping sequence of the piezoelectric clamping units in the first and second layers of the stator, the step-by-step ultra-precision rotary motion around the rotating shaft is realized. The stator is packaged with two layers of the self-centering piezoelectric clamping unit, rotary driving unit and preloading unit; the rotor is a variable interface rotating shaft, which can drive different objects by changing the connection style of the interface. The clamping unit is composed of the piezoelectric stack encapsulated in the stator and the self-centering flexure hinge. The preloading unit is utilized to pre tighten the clamping piezoelectric stack, and the clamping pressure is adjusted by adjusting the screw in length to control the engaging wedge block. The driving unit is composed of the driving piezoelectric stack, the driving indenting block and the corresponding parts of stator, which is used to apply rotating torque to the first layer of stator. The maximum diameter of stator is 80 mm and the diameter of rotor is 20 mm. This proposed inchworm type piezoelectric actuator could achieve stable stepping rotation output. The size of the driving voltage will affect the single-step rotation angle of the rotor: as the driving voltage increases, the rotation angle of the rotor also increases; when the driving voltage is less than 20 V, the rotor cannot work stably, so the minimum step angle of the rotor is 4.95 μrad. In the case that the driving voltage is 100 V, the maximum step angle of the rotor is 216.7 μrad. The maximum speed of the rotor is 6508.5 μrad/s, and the driving frequency is 30 Hz. The designed inchworm type piezoelectric actuator has a maximum output torque of 93.1 N·mm. **Figure 5** shows that

the driving voltage and clamping voltage are maintained at 100 V, and when the driving frequency is 1 Hz, after the rotor rotates 20 steps in the forward and reverse directions, the forward and backward error of the rotor is 0.76 μm. The total error of 20 steps is 38 μrad, so the step angle error of the inchworm type piezoelectric rotary actuator designed in this paper is 1.9 μrad.

The disadvantage of the inchworm type piezoelectric actuator is that the structure is relatively complicated. The traditional inchworm type actuator needs to use at least two clamping units and one drive unit. In this way, multiple timing controls will cause the program to be complicated, which makes the inchworm piezoelectric actuator more complicated. The application has brought unfavorable effects. Based on the above work, a simplified inchworm type piezoelectric rotary actuator was designed and manufactured by Li et al., which uses a triangular lever flexure hinge to complete the clamping and driving actions at the same time [19].

By using the triangular lever flexure hinge, one driving unit and one clamping unit could be utilized to realize stepping rotation of the rotor. Its stator is simplified from a two-layer structure to a single-layer structure, which reduces the overall height; the control adopts two-channel voltage control, which reduces the output of one clamp voltage. **Figure 6** shows the overall structure of the simplified inchworm piezoelectric actuator, which mainly includes a stator, a rotor, four drive piezoelectric stacks, two clamp piezoelectric stacks and six pre-tightening screws. The stator material is 65Mn, and the drive hinge and clamp hinge are processed by wire cutting. The rotor diameter is 20 mm. The pre-tightening screws are used to adjust the pre-tightening force of the clamping piezoelectric stack and the driving piezoelectric stack. It is seen from **Figure 6** that there is a small "jump" in the middle of each step, which is caused by the impact of the clamping unit on the rotor. When the driving voltage is 100 V and the driving frequency is 1 Hz, the maximum output torque of the designed simplified inchworm piezoelectric actuator is 19.6 N·mm. When the output load is greater than 19.6 N·mm, the rotor cannot run stably. When the driving voltage signal increases from 20 V to 100 V, the rotor step angle also increases, which coincides with the approximately proportional relationship between the output displacement of the piezoelectric stack and the driving voltage. The maximum step angle occurs when the drive voltage is 100 V and the drive frequency is fixed at 1 Hz, and the maximum step angle is 1360 μrad. When the drive voltage is less than 20 V, the simplified inchworm piezoelectric actuator cannot operate stably, so its operating resolution is 25 μrad. Contrary to the above, when the drive frequency is increased from 0 Hz to 200 Hz, the rotor step angle decreases rapidly. After 200 Hz, the rotor step angle stabilizes near a small value.

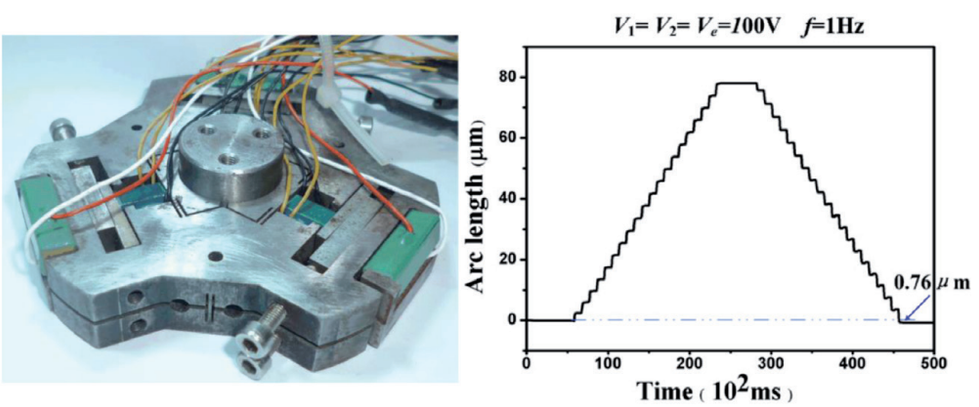


Figure 5.
Rotary inchworm type piezoelectric actuators by Li et al. [4].

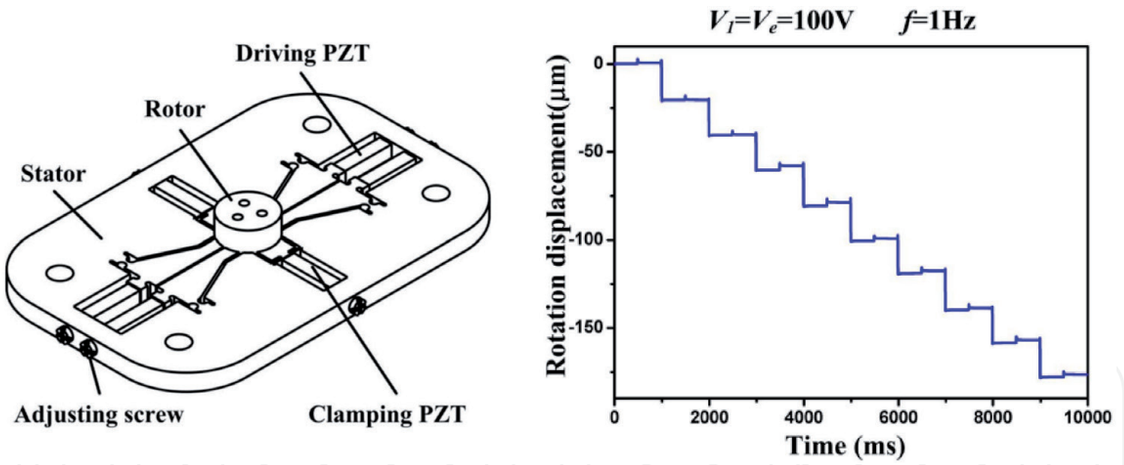


Figure 6.
Simplified inchworm piezoelectric actuator by Li et al. [19].

3.3 Multi-DOF inchworm actuator

How to obtain multi-DOF motion within a compact size is always the pursuing interest for researchers of the actuator field. Generally, same single-DOF actuators are assembled in series to achieve the so called multi-DOF motion, which brings the large structure size and assemble problems. With the help of integral flexure structure, Li et al. firstly proposed the 2-DOF inchworm piezoelectric actuator which could achieve both rotary and linear motions with a compact size, as is shown in **Figure 7** [20]. The structure of the proposed 2-DOF actuator is composed of a stator and a slider. The stator and slider are subdivided into upper, middle and lower layers. Four right-angle flexure hinges acting as torsion springs are used to overlap the upper and middle layers of the stator. The linear displacement of the positioning platform relies on four flexure hinges to connect the middle and lower layers of the stator. Moreover, according to the characteristics of PZTs that can be driven by linear motion and rotational motion, four linear driving PZTs and one rotary driving PZT are respectively arranged on the upper and lower layers of the stator. As for the slider, each layer is fixed with a single clamping PZT. Using 65Mn as the material of the stator and slider to obtain higher elasticity, the device needs to be vacuum heat treated.

The positioning platform can realize linear movement and rotational movement according to different numbers of piezoelectric ceramics, placement

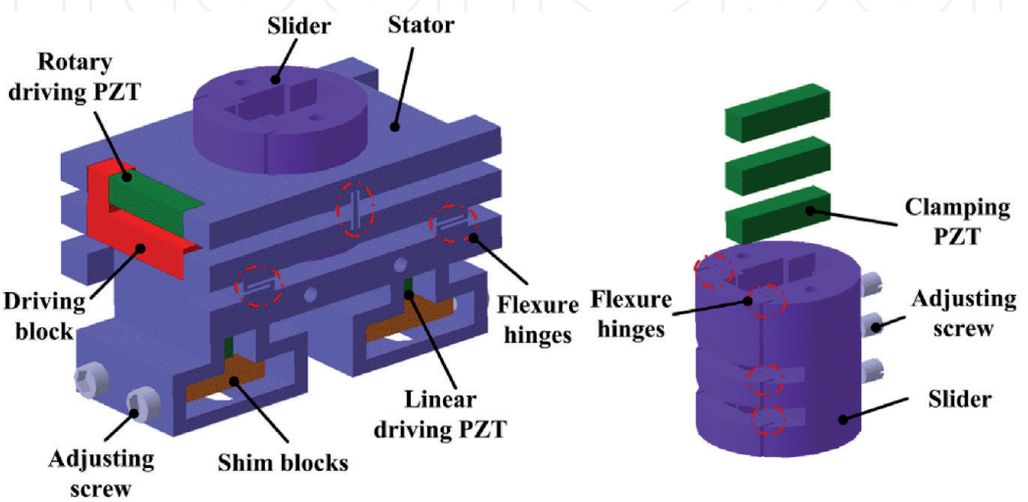


Figure 7.
Graphic model of the 2-DOF inchworm piezoelectric actuator [20].

positions and flexible hinges. For the rotary motion, the proposed actuator operates stably under a driving voltage of 100 V to 6 V. In the case that the driving voltage is reduced from 100 V to 6 V, the rotation angle of 10 steps decreases. This result may be that the degree of PZT expansion is directly proportional to the input voltage. In addition, with the lowering of the driving voltage, the amplitude of the first-order oscillation decreases from 28.20μrad to 3.75μrad. During the down-regulation process, it is found that the step displacement of the platform is shortened and the fluctuation amplitude is larger. The platform cannot work stably when the driving voltage is lower than 6 V. According to the total rotation angle of 4.52μrad, 20 steps, the minimum step angle is 0.23μrad. It indicates that this inchworm positioning platform has good performance under constant driving frequency and driving voltage. Under the condition of controlling the driving frequency, the speed increases with the increase of the driving voltage. When f = 21 Hz, the speed reaches the peak value. When f = 20 Hz and U = 100 V, the maximum speed is 3521.70 μrad/s. However, when the frequency is higher than 21 Hz, the mechanical structure of the drive cannot normally respond to the electrical signal. The energy conversion method can be explained as that the structure cannot convert all the electrical energy into mechanical energy due to the high frequency, and there will be a certain energy loss.

For the linear motion, the designed inchworm actuator works continuously under a constant driving voltage of 10 V to 100 V. Under the driving voltage U = 100 V, the total displacement of the actuator in 10 steps is 82.30 μm, and the available single-step displacement is 8.23 μm. In the case that the input voltage is lower than 10 V, the actuator cannot work normally. According to the total rotation angle of 3.05μrad, 20 steps, the minimum step angle is 0.15 μm. The speed characteristics of the linear motion of the actuator under the clamp voltage have been mentioned. According to the experimental data, as the frequency increases, the speed increases. When the frequency is greater than 26 Hz, the speed gradually decreases. When f = 26 Hz and U = 100 V, the maximum speed is 105.31 μm/s.

3.4 Comparison

As shown in **Table 1**, three types of inchworm actuators all obtain large output force/torque and stroke, high resolution. Previous studies indicate that all types are able to realize the output force/torque of several to dozen newton/newton metre. The resolution scales of them all attain micrometer/microradian and based on its working principle, repeating the displacement output under the periodic signal, their stroke are all very large. Linear inchworm actuator is able to attain a high speed of 30 mm/min and rotary inchworm actuator achieves a high speed of 6508.5 μrad/s while Multi-DOF inchworm actuator is slower. To achieve the aim of multi-DOF, the structure of Multi-DOF inchworm actuator is also more complicated with a slower response.

Type	Structure	Motion type	Output speed	Output force/torque	Stroke
Linear	Simple	Linear	Large	Large	Large
Rotary	Medium	Rotary	Large	Large	Large
Multi-DOF	Complicated	Multi-DOF	Medium	Large	Large

Table 1.
Characteristics comparison of different inchworm actuators.

3.5 Applications

Over the past years, the inchworm actuator has been widely applied in some commercial areas. High resolution is one of the most significant advantages of the inchworm actuator. Therefore, ultra-precision manufacturing technology, precision focusing system and micro-robot obtains wide range use of inchworm actuator as their actuation sources [21–22]. When coupled with large output force/torque, the inchworm actuator is also widely used in medical engineering areas like drug delivery, cell manipulation, lab on a chip [23–24]. Compared with other piezoelectric actuators, the advantage of long stroke also employs inchworm actuator in precision position platform [25].

4. Future direction

4.1 Simplified structure

One of the significant shortcomings of inchworm type piezoelectric is the complex structure which brings trouble for the manufacture and control. **Figure 8** shows the structure of the proposed simplified piezoelectric actuator based on the parasitic movement of the flexure mechanism by Li et al. [26]. With the help of the parasitic movement of the flexure mechanism, only two piezoelectric elements are needed. It is mainly composed of the base, the slider, piezo-stack 1, piezo-stack 2, flexure mechanism 1, flexure mechanism 2, two wedge blocks, four micrometer knobs and eight screws. Piezo-stack 1 (AE0505D16, 5 × 5 × 20 mm, NEC/TOKIN CORPORATION) is inserted into the flexure mechanism 1 through the wedge block to push the linear slider. The assembly process of the piezoelectric stack 2 and the flexure mechanism 2 are the same. The high-precision four-micron knob (M6 from SHSIWI) is utilized to adjust the preloading force between the flexure mechanism and the slider. The slider is a commercial linear guide with high linearity produced by THK. The flexure mechanism is made of aluminum alloy AL7075 manufactured by WEDM. Screws are applied to stably assemble all components on the base. The overall size of the proposed stepping piezoelectric actuator is 100 mm × 60 mm × 18 mm.

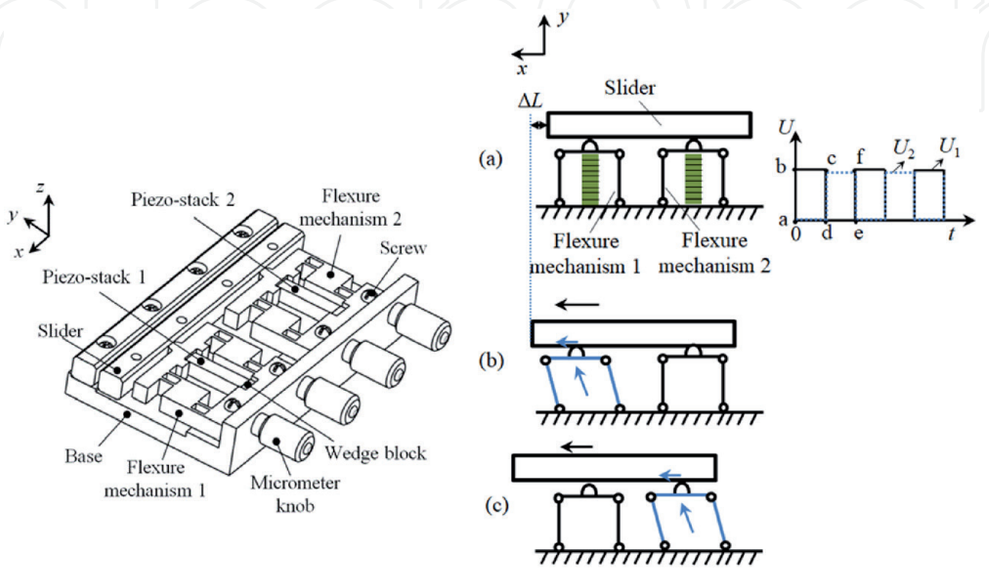


Figure 8.
Structure of the proposed simplified piezoelectric actuator and motion principle [26].

Two piezoelectric "legs" are required to alternately drive the slider, and this is why they are sometimes called "walking" type piezoelectric actuators. In addition, for traditional "walking" type piezoelectric actuator, in each piezoelectric "leg", at least two piezoelectric elements are required (one for flexure movement and one for longitudinal movement). The movement principle of the stepping piezoelectric actuator is the "circular movement" of the piezoelectric "legs". In short, each piezoelectric "leg" should achieve two movements in x and y directions.

In the proposed study by Li et al., the parasitic movement of the flexure mechanism is applied to simplify the entire system. Generally, the piezo-stack could only achieve the one motion in its longitudinal direction. Whereas, as shown in **Figure 8(b)**, with the aid of the asymmetrical flexure mechanism, the piezo-stack will generate an oblique upward force, which causes the motion displacement in both x and y directions. The parasitic movement L_x in x direction is used to drive the linear movement of the slider. However, only one flexure mechanism cannot achieve walking motion, and at least two flexure mechanisms ("legs") are required. In addition, during the movement, the input square wave voltages U_1 and U_2 have the same magnitude but different phases. The experimental results display that the application of the parasitic motion of the flexure mechanism is able to simplify the inchworm type piezoelectric actuator. The stepping motion of the proposed actuator requires only two piezoelectric elements and two input signals. Additionally, performance of the proposed simplified piezoelectric actuator (stepping performance, speed performance, and load performance) has a certain relationship with the input voltage and frequency. Under the conditions of U = 100 V and f = 1 Hz, the maximum step displacement ΔL = 1.75 μm. Under the condition of U = 30 V and f = 1 Hz, the minimum step displacement ΔL = 0.18 μm. When U = 100 V, f = 20 Hz, the maximum movement speed V_s = 39.78 μm. This study verifies the feasibility of design and simplification of inchworm type piezoelectric actuators with parasitic motion of flexure mechanisms, and provides a new idea for the research of piezoelectric actuators. Potential applications in optical engineering and cellular operating systems require more work.

4.2 Simplified control

For most of the inchworm type piezoelectric actuators, three input signals are necessary for one driving unit and two clamping units, which make the control system also complicated. In order to simplify the control system, Gao et al. proposed one novel piezoelectric inchworm actuator which uses a DC motor to drive the permanent magnet for alternate clamping, applies a laser beam sensor to detect the position of the permanent magnet and generates an excitation signal to drive the piezoelectric stack [27]. The actuator only needs a DC signal to drive and can adjust the frequency by changing the motor speed. The movement mechanism of the actuator is emphatically discussed, and the influence of the permanent magnet structure on the clamp is studied. The flexibility matrix method and COMSOL finite element software are used to simulate and analyze the flexure hinge. The driving signal for the piezoelectric stack is generated by self-sensing and automatically adapts to the frequency change, which simplifies the control signal of the inchworm actuator. The use of the magnetic clamping unit solves the serious friction and wear problems of the current clamping method of piezoelectric inchworm actuators. In addition, the driving unit and clamping unit of the proposed piezoelectric inchworm actuator are tested experimentally. The experimental results confirm the feasibility of the proposed scheme and obtained relevant optimized structural parameters.

The overall structure of the proposed actuator, as shown in **Figure 9**, is mainly composed of a sensing unit, a driving unit and a clamping unit. As shown

in **Figure 9(a)**, the clamping unit is mainly composed of a DC motor, a motor base, a permanent magnet after magnetization (RPM, red), a permanent magnet before magnetization (NRPM, blue), bearings and a bearing housing. As shown in **Figure 9(b)**, the sensing unit includes a cam, a laser beam sensor (OLS) and a bracket. The driving unit includes a flexible hinge mechanism with integrated piezoelectric stack (AE0505D16, NEC/TOKIN CORPORATION), a wedge-shaped adjusting mechanism (built-in a pair of wedges and a pre-tightening bolt) and a slider, as shown in **Figure 9(c)**. The designed slider can slide in the sliding groove of the flexible hinge mechanism. Two clamping modules and cams are fixed at the end of the output shaft of the DC motor, and each clamping module is assembled by a radially polarized permanent magnet RPM and a non-radially polarized permanent magnet NRPM. The piezoelectric stack is preloaded by the wedge-shaped adjusting mechanism and nested in the installation slot of the flexible hinge mechanism. The laser beam sensor is supported by two brackets and generates an excitation signal by detecting the position of the cam. In addition, the support block, the DC motor and the bearing are assembled on the base with eight bolts.

The proposed inchworm actuator by Gao et al. utilizes a DC motor to drive the permanent magnet for rotating to achieve alternate clamping. The actuator does not need to input the driving voltage signal of the piezoelectric stack. It only senses the position of the permanent magnet through the laser beam sensor, and generates an excitation signal to drive the piezoelectric stack to achieve precise linear displacement output. Its working principle is shown in **Figure 10**. Work performance of

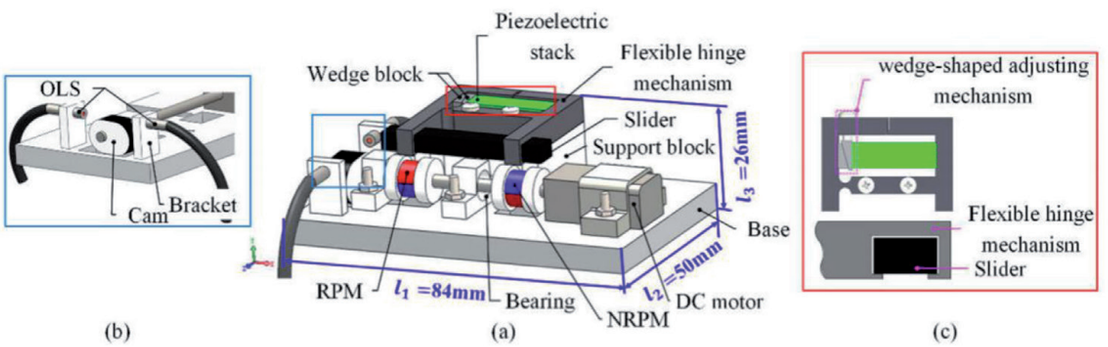


Figure 9.
Structure of the actuator by Gao et al.: (a) sensing unit; (b) sensing unit; (c) driving unit [27].

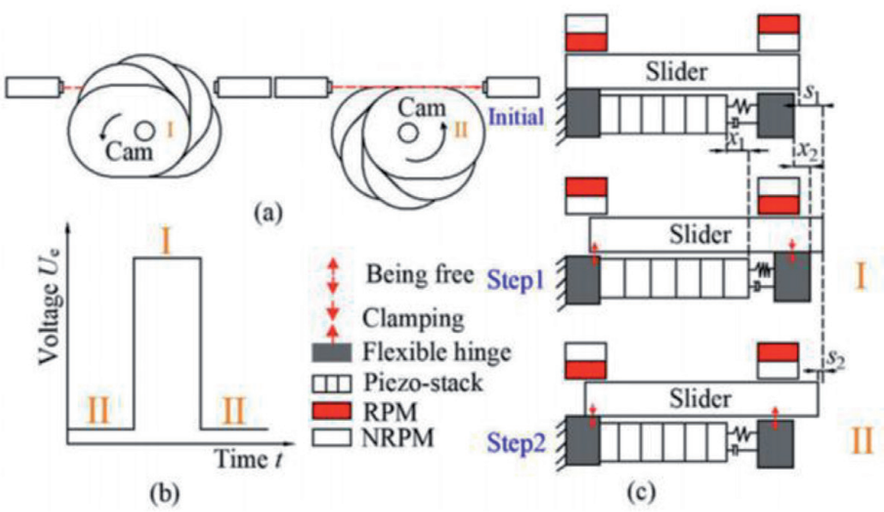
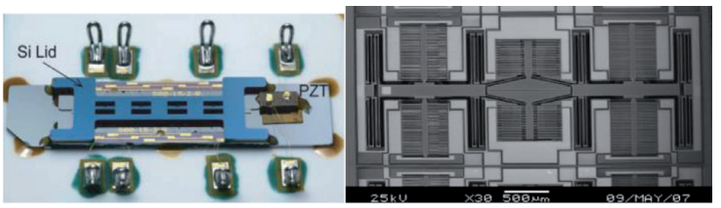


Figure 10.
Working principle of the inchworm piezoelectric actuator with simplified control system by Gao et al. [27].



(a) (b)

Figure 11.
Miniaturized inchworm type actuators: (a) by Risaku et al. [28]; (b) by Mehmet et al. [29].

the proposed actuator was studied carefully. For the important component of the driving unit, the "Z" type flexure hinge, the flexibility matrix method is used to perform theoretical calculations. The error between the simulation results and the theoretical calculation results is about 2.13%, indicating the accuracy of the calculation; for the magnetic clamping unit, when the clamping distance is 1 mm, the magnetic clamping unit has better clamping capability. The experimental results show that the actuator has a good linear displacement. When U_e = 150 V and f = 40 Hz, its maximum movement speed is 481.43 μm/s, and the maximum load is m = 950 g.

4.3 Other directions

The inchworm type piezoelectric drive device can not only obtain large output stroke, but also ensure high output accuracy and load-carrying capacity, which is favored by many scholars. The research of Inchworm piezoelectric driving device has its own characteristics at home and abroad, which provides a favorable technical basis for the development and application of piezoelectric precision drive technology. Besides the above future directions, the existing inchworm piezoelectric actuator is still in the stage of empirical design and test, lacking of relevant theoretical model guidance, and there are problems of empirical design and repeated attempts. Therefore, it is necessary to establish the dynamic model of the inchworm piezoelectric actuator to guide the design and research of the inchworm piezoelectric drive device. In addition, the miniaturization is always the hot point for piezoelectric actuators which could leads to the real application in many research and industrial fields.

Risaku et al. have developed a large stroke and high precision inchworm actuator [28] (**Figure 11**). With the combination of piezoelectric and electrostatic motion principles, the displacement accuracy of each step reaches tens of nanometers, which can be called ultra-high precision. The displacement accuracy is 59 nm/cycle, but the maximum travel distance is only 600 μm, which needs to be improved.

In order to solve the shortcomings that most inchworm type piezoelectric actuators require larger input voltage, Mehmet et al. took the lead in developing a new type of low voltage, largestroke, and large output inchworm actuator based on the micro-electromechanical systems (MEMS) [29]. It mainly applies the principle of electrostatic motion. Through the amplification of the flexible hinge, it achieves a total displacement of ±18 μm and an output force of ±30 μN at a low voltage of 7 V; a displacement of ±35 μm can be achieved at a voltage of 16 V, ±110 μN output force.

5. Conclusion

The inchworm movement is a high-precision driving method that imitates the movement form of the inchworm in nature to realize the stepping movement of itself or the holding object. Inchworm movement is a kind of stepping movement,

which is different from other continuous movement. Its movement can be regarded as a combination of movement and stop in time, but it is also a continuous movement from the perspective of the overall effect of the movement. Inchworm motion can easily achieve large-stroke step-by-step linear motion. Although scholars in various countries have conducted a number of research work on inchworm-type piezoelectric driving devices, most of their research content is linear inchworm driving devices, which involve rotation. There are few reports on the inchworm actuator, and the existing inchworm-type piezoelectric actuator has complex structure control, lacks relevant theoretical model guidance, and has problems of empirical design and repeated attempts. In the future, there is still a lot of work to be solved for the inchworm piezoelectric actuator to promote the real practical use of the inchworm piezoelectric actuator.

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Author details

Jianping Li*, Jianming Wen, Yili Hu, Zhonghua Zhang, Lidong He and Nen Wan
The Institute of Precision Machinery and Smart Structure, College of Engineering, Zhejiang Normal University, Jinhua, Zhejiang, China

*Address all correspondence to: lijp@zjnu.cn

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References

[1] M. W. Fairbairn, S. R. Moheimani, Fleming, A. J. Q Control of an Atomic Force Microscope Microcantilever: A Sensorless Approach, J. Microelectromech. S., 20(6) (2011) 1372-1381.

[2] Q. Li, L. Liu, X. Ma, et al, Development of Multi-target Acquisition, Pointing and Tracking System for Airborne Laser Communication, IEEE T. Ind. Inform. 15(3) (2018) 1720-1729.

[3] Y. Peng, X. Gu, J. Wang, H. Yu, A review of long range piezoelectric motors using frequency leveraged method, Sensor. Actuat. A: Phys. 235 (2015) 240-255.

[4] J. Li, H. Zhao, H. Qu et al, A piezoelectric-driven rotary actuator by means of inchworm motion, Sensor. Actuat. A: Phys. 194 (2013) 269-276.

[5] C. Moon, S. Lee, J. K. Chung, A new fast inchworm type actuator with the robust I/Q heterodyne interferometer feedback, Mechatronics 16(2) (2006) 105-10.

[6] Li J , Huang H , Morita T . Stepping Piezoelectric Actuators with Large Working Stroke for Nano-positioning Systems: A Review[J]. Sensors and Actuators A Physical, 2019, 292:39-51.

[7] B. Zhang, Z. Zhu, Developing a linear piezomotor with nanometer resolution and high stiffness, IEEE/ ASME Trans. Mechatron. 2(1) (1997) 22-29.

[8] D. Newton, E. Garcia, G.C. Horner, A linear piezoelectric motor, Smart Mater. Struct. 7(3) (1998) 295.

[9] S. Hua, G. Liu, X. Wang, Y. Wang, J. Li, A Piezoelectric Inchworm Actuator with Bidirectional Thrust Force, Sensors & Transducers, 171(5) (2014) 169.

[10] G. R. Stibitz, Incremental feed mechanisms, US Patent US3138749 (1964).

[11] S. K. Hsu, A. Arbor, A. Blatter, Transducer, US Patent US3292019 (1966).

[12] A.D. Brisbane, Position control device, US Patent US 3377489 (1968).

[13] W. Chen, Y. Liu, Y. Liu et al, Design and experimental evaluation of a novel stepping linear piezoelectric actuator, Sensor. Actuat. A: Phys. 276 (2018) 259-266.

[14] C. Moon, S. Lee, J. K. Chung, A new fast inchworm type actuator with the robust I/Q heterodyne interferometer feedback, Mechatronics 16(2) (2006) 105-10.

[15] T. Fujimoto, Linear motor driving device, US Patent US4736131 (1988).

[16] Y. Kim, S. Choi, J. Park et al, The characteristics of variable speed inchworm stage using lever mechanism by different materials, J. Nanosci. Nanotechno. 8(11) (2008) 5696.

[17] Yang Shuchen, Liu Jianfang, Yang Zhigang, et al. Research on external driven bidirectional thrust piezoelectric stepping precision actuator [J]. Optical precision engineering, 2006. (In Chinese)

[18] S. Kim, S. Kim, Precise rotary motor by inchworm motion using dual wrap belts, Rev. Sci. Instrum. 70(5) (1999) 2546-50.

[19] Li J , Zhao H , Shao M , et al. Design and experiment performances of an inchworm type rotary actuator[J]. Review of Scientific Instruments, 2014, 85(8):256.

[20] J. Li, H. Zhao, X. Qu et al, Development of a compact 2-DOF

precision piezoelectric positioning platform based on inchworm principle, Sensor. Actuat. A: Phys. 222 (2015) 87-95.

[21] Mohith S , Upadhya A , Navin K P , et al. Recent trends in piezoelectric actuators for precision motion and their applications: a review[J]. Smart. Mater. Struct. 2021, 30(013002).

[22] Wang L , Chen W , Liu J , et al. A review of recent studies on non-resonant piezoelectric actuators. Mech. Syst. Signal. Pr, 2019, 133(106254).

[23] Wang S , Rong W , Wang L , Xie et al. A survey of piezoelectric actuators with long working stroke in recent years: classifications, principles, connections and distinctions. Mech. Syst. Signal. 2019, 123: 591-605.

[24] Wang P , Xu Q . Design and testing of a flexure-based constant-force stage for biological cell micromanipulation. IEEE Transactions on Automation Science and Engineering, 2017 99: 1-13.

[25] Shubao S , Siyang S , Minglong X , Wenjian J . Mechanically reconfigurable reflector for future smart space antenna application. Smart. Mater. Struct. 2018 (accepted). DOI: 10.1088/1361-665X/aad480.

[26] Wen J , Wan N , Wang R , et al. A Novel Linear Walking Type Piezoelectric Actuator Based on the Parasitic Motion of Flexure Mechanisms[J]. IEEE Access, 2019:1-1.

[27] Gao Y , Wen J , Ma J , et al. A self-adapting linear inchworm piezoelectric actuator based on a permanent magnets clamping structure[J]. Mechanical systems and signal processing, 2019, 132(Oct.1):429-440.

[28] Risaku, Toda, Eui-Hyeok, et al. A normally latched, large-stroke, inchworm microactuator[J]. Journal of Micromechanics and Microengineering, 2007, 17(8).

[29] Erismis M A , Neves H P , Puers R, et al. Saw-tooth vernier ratchets for electrostatic inchworm actuators[J]. Sensors & Actuators A Physical, 2009, 156(1):66-71.