Chapter

# Parasitic Motion Principle (PMP) Piezoelectric Actuators: Definition and Recent Developments

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## Abstract

Stepping piezoelectric actuators have achieved significant improvements to satisfy the urgent demands on precision positioning with the capability of long working stroke, high accuracy and micro/nano-scale resolution, coupled with the merits of fast response and high stiffness. Among them, inchworm type, friction-inertia type, and parasitic type are three main types of stepping piezoelectric actuators. This chapter is aimed to introduce the basic definition and typical features of the parasitic motion principle (PMP), followed by summarizing the recent developments and achievements of PMP piezoelectric actuators. The emphasis of this chapter includes three key points, the structural optimization, output characteristic analysis and performance enhancement. Finally, the current existing issues and some potential research topics in the future are discussed. It is expected that this chapter can assist relevant researchers to understand the basic principle and recent development of PMP piezoelectric actuators.

**Keywords:** parasitic motion principle, piezoelectric actuator, long working stroke, flexure hinge-based compliant mechanism, backward motion

## 1. Introduction

Nowadays, long working stroke precision positioning systems with micro-to-nano resolution are significantly demanded in many scientific studies and industrial fields [1–3]. Most of the conventional actuators can hardly satisfy the requirements on positioning resolution for precision positioning systems, such as hydro-motors, direct/alternating current motors, pneumatic elements, et al., even with the merits of large output capability, fast response, and long working stroke [4–6].

The piezoelectric actuator is one of the potential alternatives for high-resolution precision positioning systems [7–10]. Up to now, various of piezoelectric-driven positioning systems with flexure hinge-based compliant mechanisms have been developed and widely applied in many scientific and industrial applications, such as atomic force microscopy (AFM) [11–13], fast tool servo (FTS) single-point diamond turning [14–16] and optical adaptive mirror [17–19], et al. Generally, restricted by the inverse piezoelectric effect of current piezoelectric materials, the displacement of a single piezoelectric element is limited within tens of nanometers to several micrometers [20]. The applications of such positioning stages are only employed within limited scopes due to micro-scale working stroke. In order to extend the working stroke of piezoelectric elements, several methods have been proposed and investigated [21–23], which can be classified according to the motion principle into the direct-driven principle, ultrasonic principle, and stepping principle. Direct-driven principle is the initial application in piezoelectric actuators. With the assistance of flexure hinge-based compliant mechanisms, it is found that the working stroke can be amplified up to several times of the original displacement of a single piezoelectric element. The maximum working stroke is extended to tens of micrometers [24–26]. However, it is still not long enough for most of the applications, and furthermore complicated flexure hinge-based compliant mechanisms deteriorate the static and dynamic characteristics of the piezoelectric actuators, reducing structural stiffness and intrinsic resonant frequency. Therefore, the direct-driven principle gradually loses its popularity in the recent years. Ultrasonic principle utilizes the resonance of stators to drive the slider/rotor. However, the interfacial wear and heat generation are lack of adequate solution to date, especially in high-speed & full-load motion [27, 28]. Stepping principle realizes the long working stroke by step displacement accumulation. By this way, high-precision positioning accuracy can be achieved in long working stroke. Hence, stepping principle has attracted much attention in the piezoelectric actuator development in the recent decades.

Various of stepping piezoelectric actuators can be further classified into three motion types, involving inchworm type, friction-inertia type, and parasitic type [3, 29–31]. Inchworm type, as a kind of bionic driving type, mimics the motion principle of inchworms in nature, which alternates the clamping and driving units to move forward and backward. Thus, its control strategy, structural assembly and the motion sequence are generally complicated. Friction-inertia type refers to a kind of spontaneous jerking motion that can occur, while two mass blocks alternate between sticking to each other and sliding over each other, with a corresponding tuning the friction and inertia forces. Compared with the inchworm type, the basic structure and control system of friction-inertia type are largely simplified but associated with loss on loading capability.

Parasitic type is a new solution to acquire both long working stroke and large output capability by adopting the parasitic motion of flexure hinge-based compliant mechanisms, which is commonly restricted in previous designs [32, 33]. Up to now, tens of PMP piezoelectric actuators based on various of flexure hinge-based compliant mechanisms have been developed with great success and achievement on improving working stroke and output capability. The purpose of this chapter is to introduce the basic parasitic motion principle, review the developments and achievements in recent years, and finally point out some potential issues and current challenges in this research.

## 2. Introduction to the parasitic motion principle

Different from other kinds of motion principles, the parasitic principle belongs to a kind of dependent motion, which generally accompanies with an independent motion, as illustrated in **Figure 1(a)**. When a load F is applied at the end of a cantilever beam, it will be bent with two motion components in $x$ and $y$ directions. The motion component in $y$ direction is the major motion, which is directly induced by the load F, while the motion component in $x$ direction is called as the parasitic motion. It simultaneously occurs with the major motion, which is generally regarded as an undesired motion component in previous studies. In general, the parasitic motion is much smaller than the major motion, but this dependent motion may deteriorate positioning accuracy and lead to more issues in calibration. On the

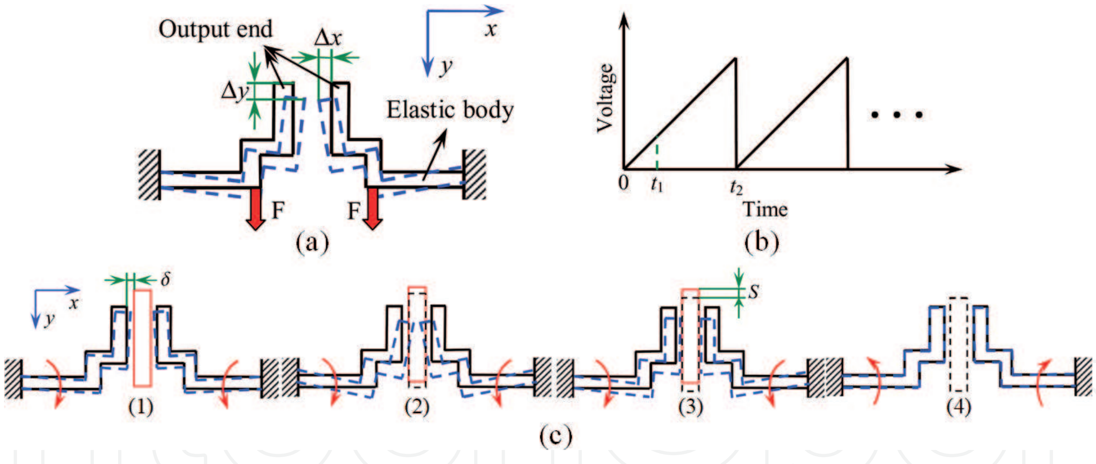


**Figure 1.**
*Schematic diagrams of the parasitic motion principle: (a) generation of parasitic motion when bending a cantilever, (b) saw-tooth wave control signal, and (c) motion principle of the PMP piezoelectric actuator in one step [23].*

other hand, if the parasitic motion of flexure hinge-based compliant mechanisms can be appropriately adopted in the design of piezoelectric actuators, it can be employed as a motion task by utilizing lower degree of freedom (DOF) with easier control, lower cost, less complexity of kinematics and simple structure. By employing specially designed control signal, for instance, the saw-tooth wave as shown in **Figure 1(b)**, applied to the piezoelectric element, the relative displacement is realized, and thus the stepping motion is achieved. Therefore, the PMP piezoelectric actuator becomes popular since its emergence in recent years.

**Figure 1(c)** shows the motion principle in one step of the PMP piezoelectric actuator. This kind of actuators is generally consisted of two sections, the stator and the slider/rotor. At the initial step (1), the stator and the slider are in separated state with an initial gap δ between each other. Then, in step (2), with a moment/force slowly applied to the flexure hinge-based compliant mechanism, the initial gap δ is filled, leading to an initial contact between the stator and the slider/rotor. Afterwards, in step (3), both the major motion and parasitic motion increase with deformation of the flexure hinge-based compliant mechanism. The slider/rotor moves in the same direction with the parasitic motion. Finally, after the slider/rotor moves to the forward displacement/angle in one step, the moment/force is suddenly removed, and the flexure hinge-based compliant mechanism recovers to its initial state and gets ready for the next cycle. In this process, as the stator still contacts with the slider/rotor, a backward motion would generally appear in the final step. Therefore, the PMP piezoelectric actuator could move with one-step displacement $\Delta S$, the one-step forward displacement minus the backward motion. By cycling from step (1) to step (4), the long working stroke can be easily achieved.

## 3. Similarities and differences with other stepping principles

Inchworm type, friction-inertia type, and parasitic type are three main kinds of motion types in stepping principle to realize long working stroke. Inchworm type, as a kind of bionic principle, employs the driving units and clamping units to obtain long working stroke. The utilization of clamping units facilitates the enhancement on output capability for piezoelectric actuators. In general, the inchworm type actuator consists of three separate parts, one driving unit and two clamping units. The moving processes of the inchworm type piezoelectric actuator are presented in **Figure 2**.

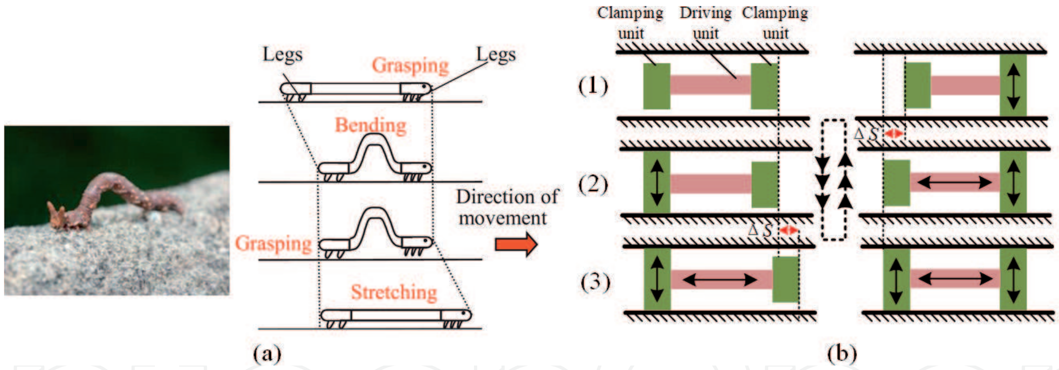


**Figure 2.**
*Motion principle of the inchworm type actuator: (a) moving principle of inchworm in nature [34], and (b) bionic stepping motion principle of inchworm type piezoelectric actuators.*

**Figure 3** shows the schematic diagram of friction-inertia type motion principle. The motion principle for the friction-inertia type follows the law of momentum conservation. A piezoelectric stack or piezoelectric bimorph, between two objects with different weights, is driven by a special control signal. At the initial step (1), the piezoelectric element is in its original status and connects two blocks. Then, in the step (2), the piezoelectric element extends gradually with the increase of driving voltage, and one block follows the movement of the piezoelectric element due to the static friction. In this process, there is no relative motion between the two objects. Afterwards, in step (3), the driving voltage suddenly drops to zero and the piezoelectric element loses power. It quickly recovers to the initial status, but the moving block remains in its position due to the inertial force. Following these steps, a small displacement occurs in this process. Based on the moving process, the friction-inertia actuator involves two motion types: impact-friction type and stick–slip type [3]. The main difference from impact-friction type is that, in stick–slip type, one end of the driving element is connected to the base and the other end drives the mass block by surface friction.

These three motion principles have some similarities and differences. According to the previous research, the performance comparison of these three motion types of stepping principle piezoelectric actuators is listed in **Table 1**. From the list, the inchworm type piezoelectric actuators dominate the high resolution and large output capability, but the free-load motion velocity is lower than its counterparts. Whereas, the friction-inertia type and parasitic type piezoelectric actuators have superiorities on motion speed and control system but deficiency on the output capability.

Compared with the inchworm type piezoelectric actuator, the structure of the PMP piezoelectric actuator is compact and its control strategy is quite simple. The parasitic motion completes the actions of clamping and driving in inchworm type motion. The re-clamping in the inchworm type is neglected in the parasitic type motion. Therefore, the difficulty and complexity on control system drop down but the output load capability is sacrificed to some extent. As a similar motion like friction-inertia type, the main difference is on the interaction between the driver and the slider/rotor. In PMP piezoelectric actuators, the normal clamping force, as well as the friction, between the driver and the slider/rotor becomes large as the voltage increases, while the forces are generally maintained the same in friction-inertia type piezoelectric actuator. All in all, the parasitic motion principle can be treated as a combination of inchworm principle and friction-inertia principle to some extent. It simplifies the structures and control strategy of inchworm principle, and exceeds the output capability of friction-inertia motion principle by increasing the clamping force.

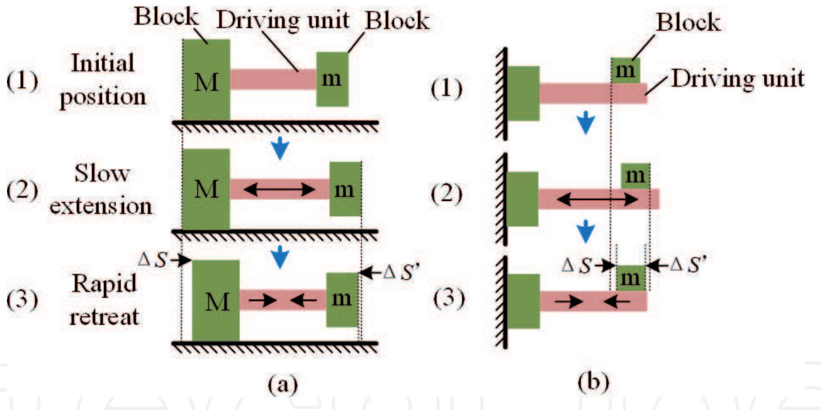


**Figure 3.**
*Motion principles of two friction-inertia types actuators: (a) impact-drive type, and (b) stick–slip type [3].*

| Type | Positioning resolution | Carrying capability | Motion speed | Control strategy |
|---|---|---|---|---|
| Inchworm | High | High | Slow | Complex |
| Friction-inertia | Middle | low | Fast | Simple |
| Parasitic | Middle | Middle | Fast | Simple |

**Table 1.**
*Performance comparison of three motion types of stepping principle piezoelectric actuators.*

## 4. Developments and achievements

In 2012, Huang et al. was the first one proposing the PMP piezoelectric actuator by using two microgrippers [23]. The three-dimension (3D) model of the actuator is shown in **Figure 4(a)**. A slider is parallelly placed between two elastic clampers. In most cases, the micro-gripper is employed to precisely manipulate micro/nano-scale objects. However, with the major motion $\Delta x$ clamping the objects, a parasitic motion $\Delta y$ pulls the slider to move a minor distance being vertical to the clamping direction. Driven by the saw-tooth wave, a long working stroke was accumulated by step-by-step motion. Various of experiments were conducted with 25 V ~ 100 V driving voltages and 1 Hz ~ 5 Hz driving frequencies to prove the practicability of the proposed driving mechanism. In another research, as shown in **Figure 4(b)**, a more compact linear parasitic motion positioning stage consisting of one compact micro-gripper and one piezoelectric element was developed by Huang et al. [35]. The experiments indicated the linear positioning stage can achieve forward and reverse movements with different driving saw-tooth waves, as well as movement velocities and stepping displacement.

By utilizing various of flexure hinge-based compliant mechanisms, some novel kinds of piezoelectric actuators based on parasitic motion are developed. **Figure 5** illustrates novel PMP piezoelectric actuators with bridge-type flexure hinge-based compliant mechanism. This type of flexure hinge-based compliant mechanism is a novel kind of structure used in piezoelectric actuators, which not only amplifies the output displacement but generates coupled motion component as well. The motion principle of the bridge-type flexure hinge-based compliant mechanism is shown in **Figure 5(a)**. Li et al. introduced both linear and rotary PMP piezoelectric actuators based on such mechanism [36, 37], as shown in **Figure 5(b)** and **(c)**. The parasitic motion of the bridge-type flexure hinge-based compliant mechanism was theoretically analyzed and numerically simulated by the elastic-beam theory (EBT), rigid-body method (RBM) and finite element method (FEM), respectively. Dual-servo

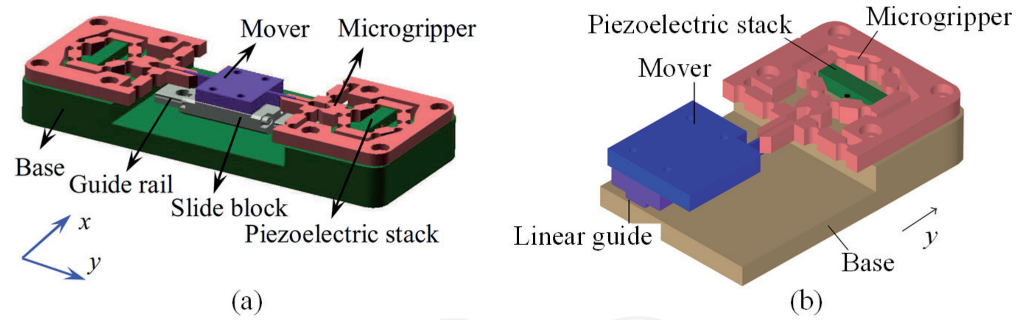


**Figure 4.**
*PMP piezoelectric actuators proposed by Huang et al. [23, 35]. (a) using two microgrippers and (b) using only one microgripper.*

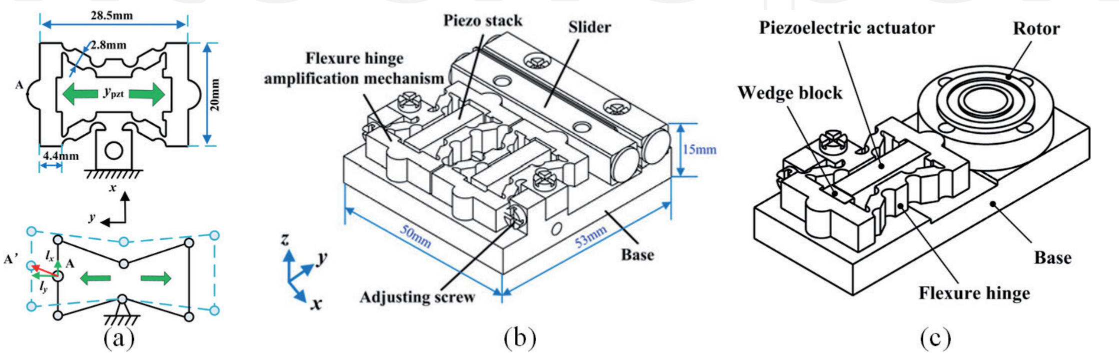


**Figure 5.**
*PMP piezoelectric actuators designed by using the bridge-type flexure hinge-based compliant mechanism: (a) working principle, (b) bidirectional linear actuator by Li et al. [37], and (c) rotary actuator by Li et al. [36].*

control strategy was introduced to achieve long working stroke and nano-scale resolution positioning within one single step. Experiments showed that the maximum velocity of 7.95 mm/s was achieved for the linear actuator with the driving voltage of 100 V at a driving frequency of 1000 Hz, while the rotary actuator can reach 32000 μrad/s with the driving voltage of 100 V at a driving frequency of 100 Hz. Wang et al. proposed a bidirectional complementary-type actuator, which utilized parasitic motion in the longitudinal deformation for driving and clamping [38]. Compared with the current existing prototypes, it reduced the motion coupling to 4%, and optimized the step consistency and driving capability to a large extent.

After that, several different PMP piezoelectric actuators are proposed by employing different flexure hinge-based compliant mechanisms, i.e. asymmetric flexure hinge-based compliant mechanism, parallelogram flexure hinge-based compliant mechanism and trapezoid flexure hinge-based compliant mechanism. In comparison with the bridge-type flexure hinge-based compliant mechanism, the asymmetric flexure hinge-based compliant mechanism has simple structure with high stiffness. Li et al. proposed an asymmetric flexure hinge-based compliant mechanism, as shown in **Figure 6(a)**, to amplify the parasitic motion in the PMP piezoelectric actuator [39]. By introducing the asymmetric flexure hinge-based compliant mechanism, the resolution of the proposed linear PMP piezoelectric actuator was improved to 0.68 μm. The maximum speed can reach 4.676 mm/s and the maximum output load was enhanced to 91.3 g. Another linear actuator was proposed by Li et al., as shown in **Figure 6(b)**. The lever-type piezoelectric actuator could achieve bidirectional motion driven by a single piezoelectric element [40]. Under the symmetry of 20% and 80%, the maximum forward velocity was 7.69 mm/s and maximum reverse velocity was 7.12 mm/s, respectively. Gao et al. presented a PMP piezoelectric actuator based on an asymmetrical flexure hinge-based compliant mechanism [41], as shown in **Figure 6(c)**. The authors designed

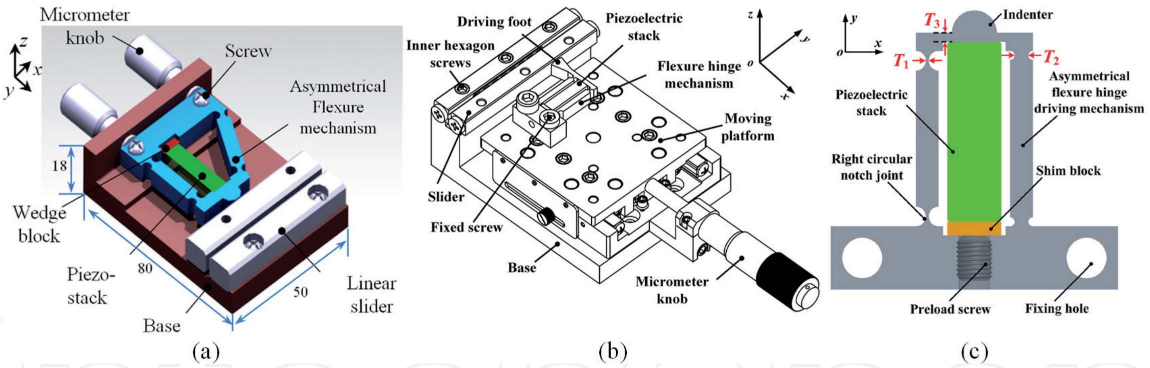


**Figure 6.**
*PMP piezoelectric actuators with the asymmetric flexure hinge-based compliant mechanism developed by (a) Li et al. [39], (b) Li et al. [40], and (c) Gao et al. [41].*

four bars with different thickness right-circle flexure hinges to achieve improvement on output speed and efficiency. Simulations were employed to optimize the structure parameters and the experimental results indicated that the maximum velocity of the proposed piezoelectric actuator reached 15.04 mm/s under the driving voltage of 100 V at a driving frequency of 490 Hz.

Parallelogram flexure hinge-based compliant mechanism is another widely used structure in PMP piezoelectric actuators. Due to its simple structure and flexible design, it gains popularity in studies. Li et al. first introduced the parallelogram flexure hinge-based compliant mechanism in the PMP piezoelectric actuators and characterized the performance of the proposed actuator [42], as shown in **Figure 7(a)**. In the case, the maximum free-load motion speed of the proposed PMP piezoelectric actuator was 14.25 mm/s under the driving voltage of 100 V at a driving frequency of 2000 Hz. Some modified parallelogram structures were also proposed with improved driving capability by Li et al. [43, 44]. By combining the parallelogram flexure hinge-based compliant mechanism and asymmetrical flexure hinge-based compliant mechanism, several different PMP piezoelectric actuators were developed, as shown in **Figure 7(b)** and **(c)**. The parasitic motion was characterized by EBT and FEM, and the experiments proved the feasibility of the proposed piezoelectric actuator and simplification of walking type for piezoelectric actuators. Furthermore, Gao et al. developed another modified parallelogram flexure hinge-based compliant mechanism in PMP piezoelectric actuators [45]. By adopting different stiffness flexure hinges, parasitic motion displacement was amplified, and the working performance was investigated by a prototype, as shown in **Figure 7(d)**.

The special mechanical properties of the trapezoid flexure hinge-based compliant mechanism attract the attention from researchers. By adjusting the structural parameters, various kinds of trapezoid flexure hinge-based compliant mechanism with different mechanics characteristics can be obtained. Some of them can easily bring in the parasitic motion in the deformation. Li et al. investigated the possibility of introducing trapezoid flexure hinge-based compliant mechanism into PMP piezoelectric actuators [46], and manufactured a prototype to study the kinematic properties of the proposed PMP piezoelectric actuator. The design of the PMP piezoelectric actuator is shown in **Figure 8(a)**. The right-circular flexure hinges with different thickness were employed in the prototype design of the trapezoid flexure hinge-based compliant mechanism, which had the capability to achieve the parasitic motion. The moving process was characterized and verified by theoretical calculation, numerical simulation and experiments. The experimental results indicated that the maximum speed was 180 μm/s with the driving voltage of 100 V at a driving frequency of 220 Hz. Cheng et al. analyzed the trapezoid flexure hinge-based compliant mechanism and applied such structure into the development

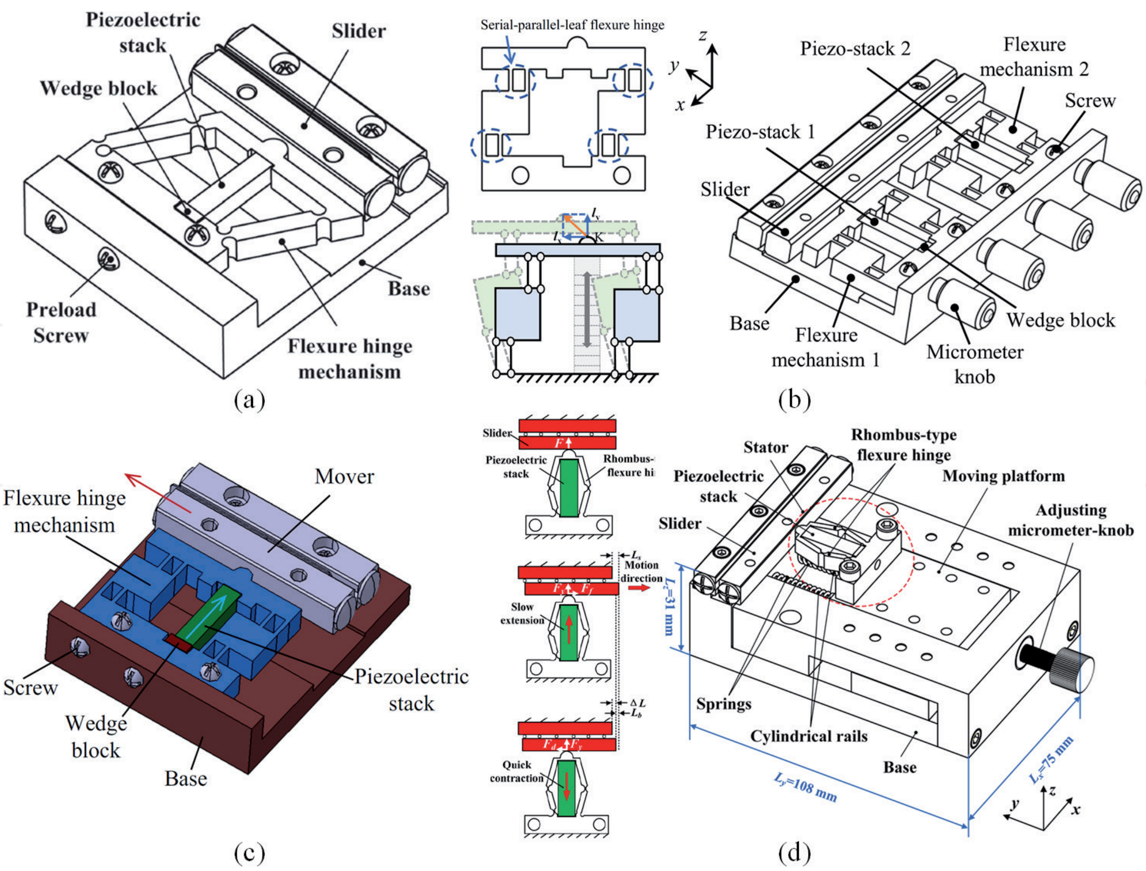


**Figure 7.**
*PMP piezoelectric actuators designed with the parallelogram flexure hinge-based compliant mechanism developed by (a) Li et al. [42], (b) Wen et al. [43], (c) Wan et al. [44], and (d) Gao et al. [45].*

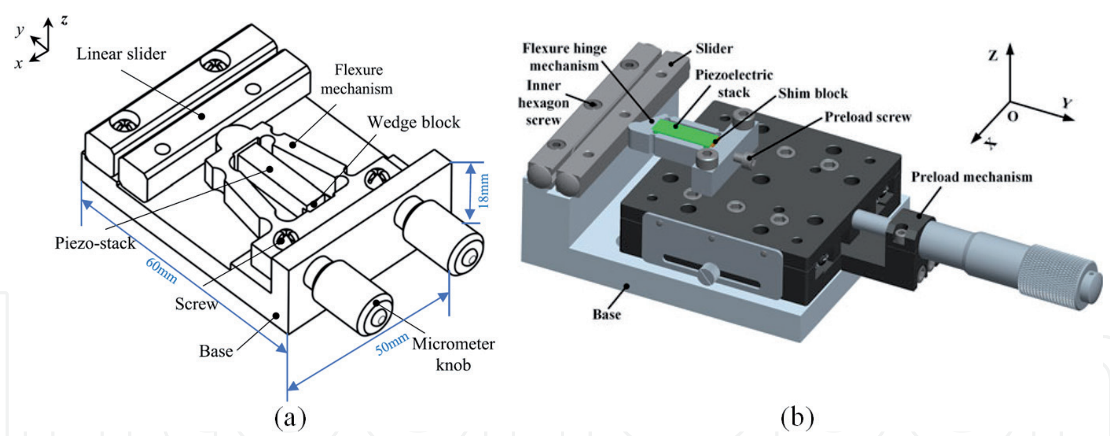


**Figure 8.**
*PMP piezoelectric actuators with trapezoid flexure hinge-based compliant mechanism: (a) equilateral triangle flexure structure by Li et al. [46], and (b) right-circular flexure structure by Cheng et al. [47].*

of PMP piezoelectric actuators [47]. They attempted to optimize the asymmetrical flexure hinge-based compliant mechanism to achieve large static friction force in slow extension phase while low kinetic friction force in quick backward phase. The prototype was fabricated to confirm the proposed structure. The maximum speed and maximum output load were 5.96 mm/s and 3 N under the driving voltage of 100 V at a driving frequency of 500 Hz. Another research employing a modified trapezoid flexure hinge-based compliant mechanism was developed by Lu et al. [48], which achieved high speed at lower driving frequency.

Apart from the most used flexure hinge-based compliant mechanism in PMP piezoelectric actuators, some other structures are also introduced to enhance the parasitic motion. The symmetrical flexure hinge-based compliant mechanism was applied into the PMP piezoelectric actuator by Yao et al. [49]. The design of the actuator is shown in **Figure 9(a)**. The structural characteristics and motion displacement were theoretically analyzed and predicted by FEM. The motion principle of the coupled symmetrical flexure hinge-based compliant mechanism is shown in **Figure 9(b)**. With the assistance of the coupled symmetrical flexure hinge-based compliant mechanism, the developed PMP piezoelectric actuator achieved notable improvement on kinematic performance and large output capability. The experiments showed that the minimum step displacement was 0.495 μm under the input driving voltage of 30 V at a driving frequency of 1 Hz and the maximum speed was 992.4 μm/s with the input driving voltage of 120 V at a driving frequency of 400 Hz. Lu et al. developed another kind of coupled symmetrical flexure hinge-based compliant mechanism for linear PMP piezoelectric actuators [50]. The FEM simulation under static load is shown in **Figure 9(c)**. The feasibility of the designed structure was confirmed by the numerical simulation and experiment.

Besides the aforementioned PMP piezoelectric actuators, Li et al. investigated a "Z-shaped" symmetric flexure hinge-based compliant mechanism in the PMP piezoelectric actuator [51]. Since the symmetric flexure hinge-based compliant mechanisms were rotated with an angle of θ = ±20° to the slider, coupled motion could be achieved in $x$ and $y$ directions. **Figure 10(a)** shows the 3D model of the PMP piezoelectric actuator. In this case, the system statics and kinetic models were established for better understanding the static and dynamic performances of the proposed linear PMP piezoelectric actuator. Furthermore, a triangular structure with flexure hinge-based compliant mechanism was proposed by Zhang et al. [52], as shown in **Figure 10(b)**. Compared to the existing actuators with similar motion principle, the proposed triangular flexure hinge-based compliant mechanism had the capability to amplify the clamping force as well as the driving force. The proposed actuator achieved several times larger driving force and higher free-load motion speed with similar or even lower driven voltage. Besides these linear PMP piezoelectric actuators, several kinds of rotary PMP piezoelectric actuators with triangular structure were proposed by Zhang et al. to confirm the possibility of the proposed flexure hinge-based compliant mechanism in PMP piezoelectric actuators [53]. To enhance the load capability for both forward and backward motions, a shared driving foot flexure hinge-based compliant mechanism, equipped with two piezoelectric stacks, was proposed by Zhang et al. [54]. The 3D model and the working principle are shown in **Figure 10(c)**. Experimental results indicated that the actuator could achieve a free-load maximum forward and backward speed up to 18.6 mm/s and 16.0 mm/s, respectively. The output capacity was largely improved to 2.0 kg for the both driving directions. Zhang et al. developed a linear piezoelectric actuator

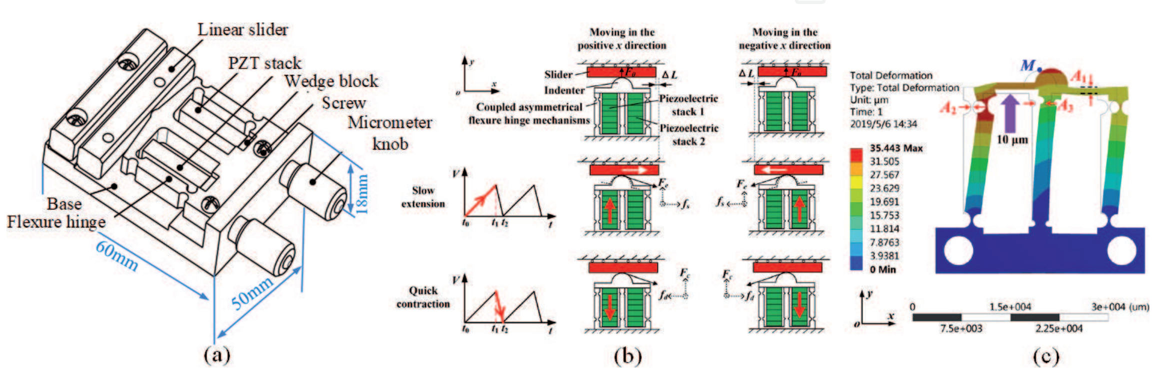


**Figure 9.**
*PMP piezoelectric actuators with coupled symmetrical flexure hinge-based compliant mechanism: (a) linear piezoelectric actuator by Yao et al. [49], (b) motion principle of the symmetrical flexure hinge-based compliant mechanism, and (c) FEM simulation by Lu et al. [50].*

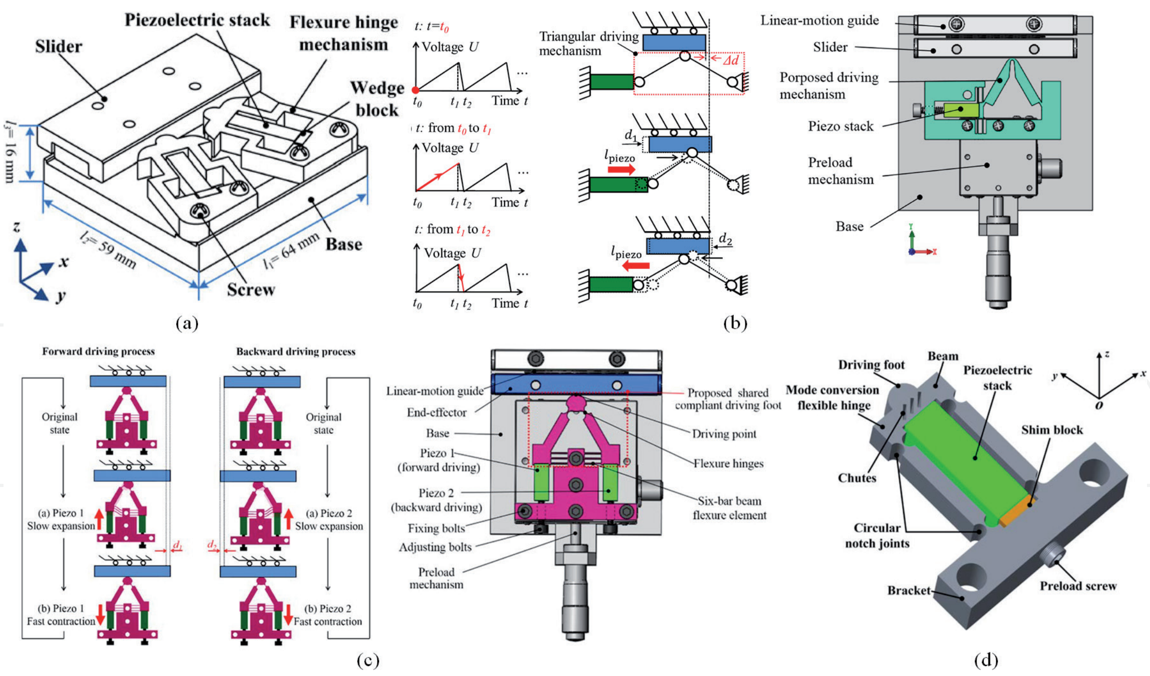


**Figure 10.**
*PMP piezoelectric actuators designed by using (a) a "Z-shaped" flexure hinge-based compliant mechanism by Li et al. [51], (b) triangular-type flexure hinge-based compliant mechanism by Zhang et al. [52], (c) shared driving foot mechanism by Zhang et al. [54], and (d) mode conversion flexure hinge-based compliant mechanism by Zhang et al. [55].*

with mode conversion flexure hinge-based compliant mechanism [55], as shown in **Figure 10(d)**. The mode conversion flexible hinge with a structure of chutes achieved lateral motion and constant phase difference with symmetrical waveform. Different parameters of the chutes were analyzed by FE simulation and experiment. The experimental results showed good agreement with the simulation analysis.

More recently, some compact flexure hinge-based compliant mechanisms are introduced into the PMP piezoelectric actuators to enhance the performances. Wang et al. reported a rotary piezoelectric actuator with centrosymmetric flexure hinge-based compliant mechanism [56]. The structure of the proposed piezoelectric actuator is presented in **Figure 11(a)**. The motion principle was analyzed by FEM, which was further confirmed by the experiment. Both the output capability and moving resolution of the proposed actuator were improved, and the clockwise and anticlockwise rotations can be switched by adjusting the driving voltage waveform. Besides the rotary PMP piezoelectric actuator, another linear PMP piezoelectric actuator was then introduced to confirm the feasibility of bidirectional PMP piezoelectric actuator [57]. The structure of the bidirectional piezoelectric actuator is illustrated in
**Figure 11(b)**. Furthermore, by employing two lever-type flexure hinge-based compliant mechanism, Li et al. developed a 2-DOF piezoelectric-driven precision positioning stage by using parasitic motion [58]. As shown **Figure 11(c)**, the stage consisted of two layers with the same driven structures and the L-shape flexure hinges made the structure compact with piezoelectric stacks being parallel to the slider. The prototype achieved relatively large output displacement over 1,600 μm with good linearity. Wang et al. developed a high-velocity rotary parasitic type piezoelectric positioner [59]. A compact rotational symmetric flexure mechanism with self-centering function was employed to generate parasitic motion to drive the rotor, as shown in **Figure 11(d)**. The experimental results showed the proposed positioning stage achieved the maximum speed of 151.4 mrad/s, which was much greater than most of the current reported non-resonant piezoelectric positioner.

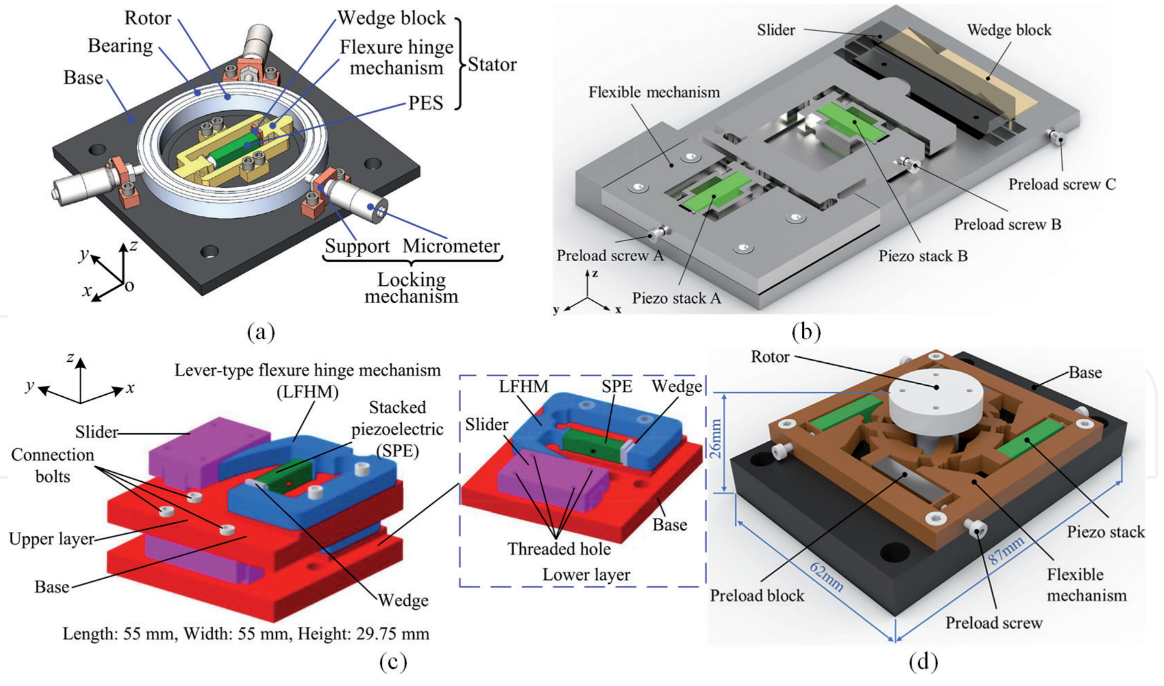


**Figure 11.**
*PMP piezoelectric actuators designed by using (a) centrosymmetric flexure hinge-based compliant mechanism for rotary actuator [56], (b) two lever-type flexure hinge-based compliant mechanism for linear actuator [57], (c) "L-shape" compact 2-DOF actuator [58], and (d) rotational symmetric flexure hinge-based compliant mechanism for rotary actuator [59].*

In order to obtain better understanding of the motion characteristics, some in-depth research is conducted to clarify the nature in some phenomena, such as backward motion and interfacial interaction. Huang et al. firstly investigated the non-linearity and backward motion in one step of a rotary PMP piezoelectric actuator [60], as shown in **Figure 12(a)**. The analysis indicated that the non-linearity in one step was due to the fit-up gap of the bearing and the self-deformation of the flexible micro-gripper when contacted with the slider, while the backward motions was attributed to the non-ideal driving wave. Furthermore, the characteristics of a linear PMP piezoelectric actuator were also investigated [61], and a dynamics model was provided for system control and optimization. Taking some potential factors, such as the coupling angle, the driving signal symmetry, the mover mass and the preload force, into consideration, the model analyzed the influences of these factors on the output, such as the step length, the backward ratio and the maximum load. Based on the characterization and analysis of the PMP piezoelectric actuators, some strategies were introduced to suppress the backward motion. Huang et al. employed two piezoelectric stacks to realize the synergic motion principle [62]. One of the piezoelectric stacks was used for driving and the other was used for lifting, as shown in **Figure 12(b)**. By theoretical analysis and experiments, the actuator could achieve stepping displacement without backward motion with the aid of synergic driving principle. Another strategy on suppression of backward motion in PMP piezoelectric actuators was by means of the sequential control method [63]. As shown in **Figure 12(c)**, two flexure-based hinge mechanisms with different displacement amplification rates in $x$ and $y$ directions were responsible for driving and lifting, respectively. Compared with some conventional PMP piezoelectric actuators, the backward motion was suppressed under the sequential control method.

Up to now, more detailed phenomena in PMP piezoelectric actuators are focused and analyzed to enhance the performances. Wang et al. investigated the influence of initial gap on the one-stepping characteristics of PMP piezoelectric actuators

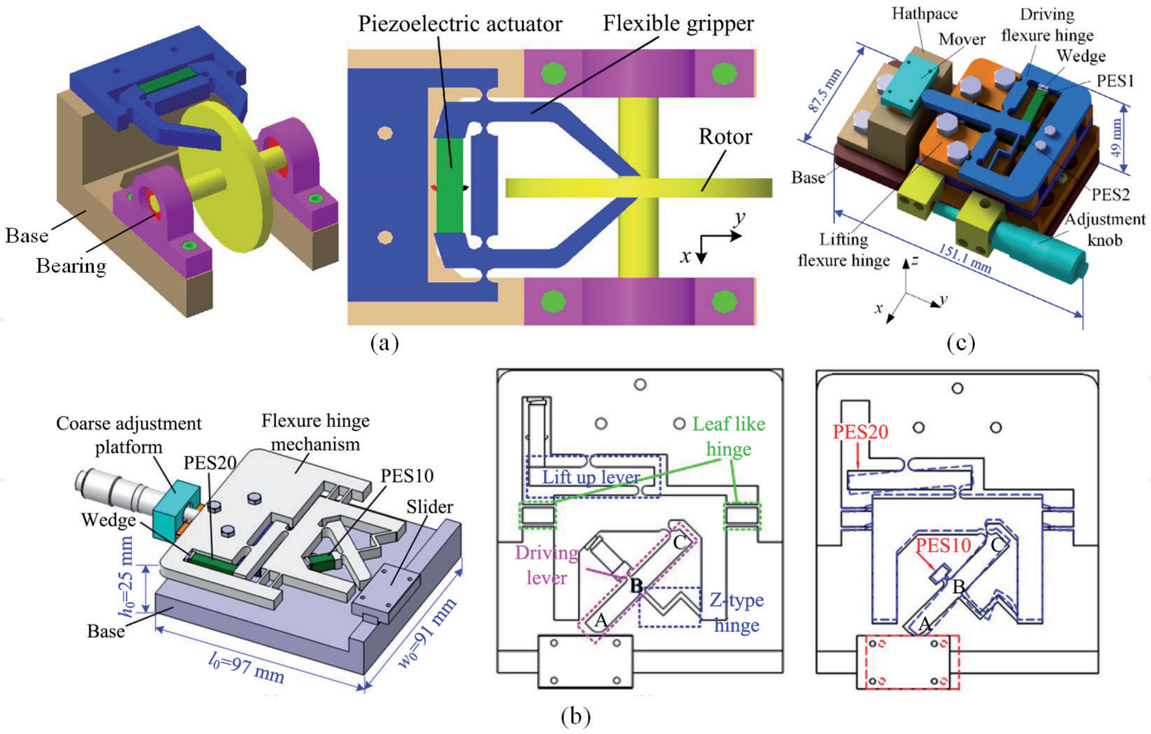


**Figure 12.**
*Mechanism investigations and further improvement on (a) non-linear and backward motion in rotary actuator [60], (b) synergic motion principle by two piezoelectric stacks [62], and (c) sequential control method to suppress the backward motion [63].*

[64]. The experimental results showed that the initial gap significantly affected the output characteristics. As shown in **Figure 13(a)**, the previous sudden return (backward motion) transformed into sudden jump, and between them, there was a transition stage, i.e. smooth motion. Another study on preloading was conducted by Yang et al. [65]. By varying the preloading between the flexure hinge-based compliant mechanism and slider, the piezoelectric actuator worked under two different motion modes. Under the new motion mode, the output performances were studied with different initial gaps, driving voltages, driving frequencies, and vertical loads. In addition, the contact force was also measured in PMP piezoelectric actuator by Xu et al. [66], as shown in **Figure 13(b)**. Since the contact force has never been quantitatively detected, it is difficult for keeping the performance uniformity of such actuator in previous studies. By integrating a cantilever beam into the driving unit for measuring the contact force, the actuator could optimize the loading capacity and motion stability by adjusting driving voltage and frequency. The experiments verified the feasibility, and the corresponding actuator was applicable.

Parasitic type piezoelectric actuator is a novel member in the family of stepping actuators. Thus, there is still a lot of research to be done to make the underlying mechanism clear, optimize the structure & control strategy, and enhance the output performances. Although several potential issues have been solved and some achievements have been obtained, the PMP piezoelectric actuators are still far from mass production and wide applications in industry. For example, the nature of the interfacial interaction, compact & simple structures to suppress the backward motion and many related issues are still the stumbling blocks on the way to completion.

## 5. Issues and future directions

With the introduction of stepping motion principle into piezoelectric actuators, positioning systems are capable to achieve long working stroke and micro-to-nano

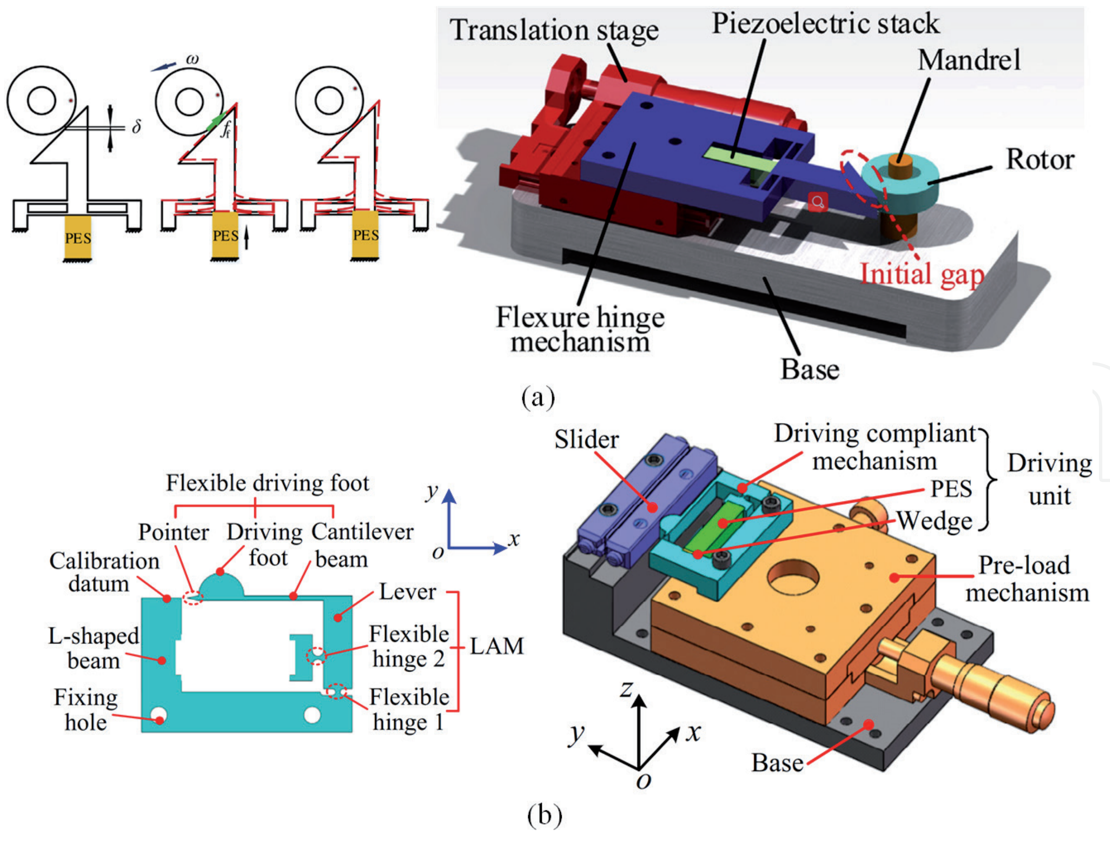


**Figure 13.**
*Mechanical and mechanism investigations on (a) initial gap for one-stepping characteristics [64], and (b) measuring the contact force [66].*

positioning resolution. Three motion types of stepping piezoelectric actuators are mostly utilized, inchworm type, friction-inertia type and parasitic type. As one of the most important types, parasitic type showcases the flexibility and massive potential in practical applications in future research and industry. In comparison with the inchworm type piezoelectric actuator, the structure and control strategy of the system are simpler, and it is much easier to obtain high free-load speed. Therefore, further research and efforts should be made to overcome the existing issues in PMP piezoelectric actuators, i.e. backward motion, to satisfy the requirements from general and specific applications, and enhance their adaptation in different conditions.

For the PMP piezoelectric actuators, which have superiorities on simple structure and control system, the low output load and intrinsic backward motions are long-existing issues due to the motion principle. Although some studies attempt to address these issues, some other issues come with the solution. For example, the suppression of backward motion came with increasing complexity of structure and control system. It is now still far from the complete to overcome these issues. Therefore, the studies on improvement of output capability and deep understanding on suppression of backward motion should be further conducted. Furthermore, since the relative motion exists in the parasitic type motion, the wear and tear damages can not be neglected, which will reduce the reliability and stability of the actuator in service. So, the deep understanding and optimization of the interfacial interaction between the flexure and the slider/rotor is another topic in future research. Finally, the multi-direction, integration and minimization of PMP piezoelectric actuators become vital for future applications. Only those which combine long stroke, large load, compact size and integrated system will gain popularity in the future precision-actuator market.

## 6. Conclusions

This chapter reviews the recent developments and achievements on PMP piezoelectric actuators. Combined with stepping motion principle, the PMP piezoelectric actuator acquires the capabilities on long working stroke and relatively large output capability, which breaks through the long-standing obstacles on micrometric working stroke of single piezoelectric element. In addition, some novel flexure-based hinge mechanisms are introduced to enhance the performances of the parasitic type motion, which not only extend the motion displacement in one step but also improve the motion stability in long working stroke. In addition, the underlying potential issues, i.e. backward motion and contact force, are investigated to understand the nature of the mechanism. By utilizing theoretical analysis and FE simulation, novel structures and driving strategies are applied to suppress the backward motion and improve the motion speed by adjusting interfacial interaction. These prototypes demonstrate better performances than previous parasitic type actuators, verifying the feasibility of the proposed methods. However, further studies should be conducted for improving the performances and overcoming current issues to satisfy the increasing demands for precision positioning and related applications.

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## Conflict of interest

The authors declare no conflict of interest.

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