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Review on Multi-Degree-of-Freedom Piezoelectric Motion Stage

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ABSTRACT Multi-degree-of-freedom (multi-DOF) piezoelectric motion stage is an important part of modern manufacturing industry. In order to perform high precision outputs in a large travel range, various multi-DOF piezoelectric motion stages have been proposed and applied for decades. This paper is concentrated on reviewing the research on a piezoelectric motion stage. It involves the major components, operating principles of different actuation modes, design schemes, and structures of the multi-DOF piezoelectric motion stages. In this paper, the summary and classification of the actuation modes used in the multi-DOF piezoelectric motion stages are presented, mainly including the resonance actuation mode, inertial actuation mode, clamping and feeding actuation mode, and direct actuation mode; the multi-DOF piezoelectric motion stage is divided into multi-actuator type and single-actuator type according to the number of actuators used in the motion stage, in which the multi-actuator type includes series, parallel, and series–parallel types from the viewpoint of structure mechanism; in addition, the output performances of the stages are compared, and the state of the arts of the stages are discussed and summarized; the further efforts and future research perspectives are highlighted.

INDEX TERMS Piezoelectric motion stage, multi-DOF, piezoelectric actuator, high precision, large travel range.

I. INTRODUCTION

Ultra-precision multi-DOF motion stage plays an important role in the fields of optical scanning, biomedicine, precision intelligent manufacturing, aerospace and so on [1]–[9], for example, cell injection based on nano-manipulation [10]–[12], micro-scanning and attitude adjustment of satellite based on nano-motion [13]–[15], fabrication of gratings and microelectronic mechanical systems based on micro-nanomachining [16]. It is required to have characteristics of compact structure, nanometer positioning accuracy, high response speed, and large travel range. An ultra-precision multi-DOF motion stage is mainly consisted of an actuation unit and an execution unit. The outputs are generally realized by two design schemes: firstly, driving the execution unit through several single-DOF actuators in series or in parallel; secondly, driving the execution unit by one multi-DOF actuator through the friction. Thus, the ultra-precision multi-DOF motion stage can be classified as the multi-actuator type and single-actuator type according to the number of actuators used. The actuator is the key unit of the whole system, and its characteristics determine the quality of the stage directly. At present, research on the actuator for the ultra-precision multi-DOF motion stage is mainly focused on two fields: the voice coil actuators [17]–[21] based on the electromagnetic effect and the piezoelectric actuators [22]–[25] based on the reverse piezoelectric effect.

The voice coin actuators [26] drive the execution unit directly by the electromagnetic force. The magnitude and direction of the electromagnetic force can be changed by adjusting the strength and polarity of the coil current. The ultra-precision driving can be achieved with the characteristics of high response speed, small size, good force characteristic and so on. It has been widely used in the ultra-precision fields. However, the stroke of voice coil actuator can only reach millimeter level due to the structure and driving principle. Besides, air bearings or magnetic suspension devices and closed loop control system are essential to meet the requirements of ultra-precision, which requires high resolution sensors and strict assembly process, resulting in complex system structure and high cost. Electromagnetic interferences in the environment also affect the accuracy. As a result, the applications of the voice coin actuators are limited. Piezoelectric actuators use the reverse piezoelectric effect of piezoelectric material to convert electrical energy into mechanical motion. They have merits of non-electromagnetic interference, self-locking at power-off state, flexible structure, fast response speed, diversified actuation modes and easy realization of nanometer resolution [27]–[31], and many scholars' attentions have been attracted.

At present, research on multi-actuator type stage has been gradually mature, and some have been commercialized [32]–[34]. From the viewpoint of mechanism, the structure of the multi-actuator type stage mainly includes series and parallel types. The series type stage uses multiple piezoelectric actuators to drive the motion stages with series structure. The input end of one stage is connected to the output end of another stage in series. In general, one-DOF output is achieved through one stage driven by a single-DOF piezoelectric actuator. The series type stage has characteristics of easy realization of large travel range and flexible actuation modes. But the vibration coupling exists among multi-DOF and superposes with each other, the accuracy cannot be guaranteed in large travel range. The parallel type stage uses multiple piezoelectric actuators to drive parallel compliant mechanism connected to the execution unit directly, and multi-DOF outputs can be achieved. Piezoelectric stacks are usually used as the actuation unit with nanometer resolution. The parallel type stage has merits of high precision, large stiffness, compact structure and large carrying capacity, has been widely studied and applied. However, the travel range is limited because the deformations of PZT stacks are only 0.1% of their lengths, in addition, the parallel structure also affects the output range.

The single-actuator type stage is usually composed of a multi-DOF piezoelectric actuator and an execution unit, which is actuated by the driving tip of the actuator, and the multi-DOF outputs can be realized by friction forces between them [35]–[37]. It has characteristics of flexible structure, high output speeds and easy realization of large travel range. But research is mainly concentrated on multi-DOF actuators operating in resonance actuation mode, the resolution is limited due to the heating and wear problems.

There are many designs for multi-DOF piezoelectric motion stages. In the literature, the research works of different actuation modes for the piezoelectric actuators and multi-actuator type stages constructed with compliant mechanisms have been well developed and concluded [38]–[43]. In this work, the related research of actuation methods for multi-DOF piezoelectric motion stages, and their structures used in the designs is surveyed, the performances of the developed stages operating in different actuation modes are compared, the state of arts of the stages are discussed, it provides a reference for future work.

The following sections of the work are organized as follows. Section 2 gives a brief introduction of the actuation modes of the piezoelectric motion stage. Section 3 presents the multi-actuator type piezoelectric stage, including the series, parallel and series-parallel types. Section 4 presents the single-actuator type piezoelectric stage, mainly on the multi-DOF piezoelectric actuators. Section 5 discusses the current problems of the stages, and the efforts made by researchers to overcome these problems in recent years. At last, conclusions and future research directions of multi-DOF piezoelectric motion stage are given in section 6.

II. ACTUATION MODES

With many years of research, there are many actuation modes for the piezoelectric motion stages, mainly including the resonance actuation mode, inertial actuation mode, clamping and feeding actuation mode, and direct actuation mode. In this section, different actuation modes are introduced and their operating principles are summarized.

A. RESONANCE ACTUATION MODE

The resonance actuation mode uses the dynamic friction force as the driving force, in which the operating frequency is usually at ultrasonic range. According to the vibration modes induced by piezoelectric ceramics, the vibration modes of the metal substrate can be divided into the standing wave type, traveling wave type and compound vibration mode type [28].

1) STANDING WAVE TYPE

A standing wave vibration is induced in the elastic substrate by applying a sine voltage excitation signal with the resonance frequency of the actuator. By placing the driving feet in specific position of the standing wave (usually, they are set between the wave loop and the wave node), the driving feet will move in oblique line trajectories, and drive the runner through friction [44]–[46]. As shown in Fig. 1, the driving feet operate with oblique lines, the runner is moved alternately by the feet. The standing wave piezoelectric actuators have merits of simple structure and simple exciting signal, but they are only suitable for uni-directional motions. Although some standing wave piezoelectric actuators have achieved bi-directional motions by two different modes [44], [47], there are obvious discrepancy between the output speed and force of the two directions.

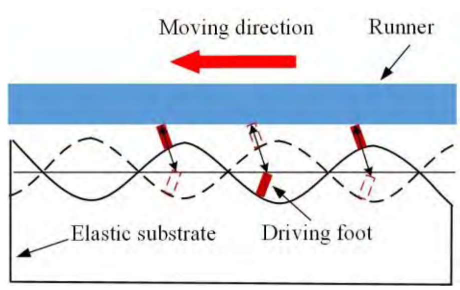

FIGURE 1. The standing wave type actuation mode [44].

2) TRAVELING WAVE TYPE

For a traveling wave type piezoelectric actuator, a flexural traveling wave is generated in the elastic substrate by the superimposition of two standing waves: these two standing waves should have the same wave number, the same frequency, the same vibration amplitude, a temporal shift of 90 degree and a spatial distance of a quarter wave length. Driving feet are placed on the surface of the elastic substrate, and move with elliptical trajectories, then, the runner is moved by friction force generated between the driving feet and itself [48], as shown in Fig. 2. Most of traveling wave type piezoelectric actuators have ring-shape or cylinder shape metal substrates [49]–[52], they need two exciting signals: a sine one and a cosine one, and they can achieve the same mechanical output performances for the bi-directional motions.

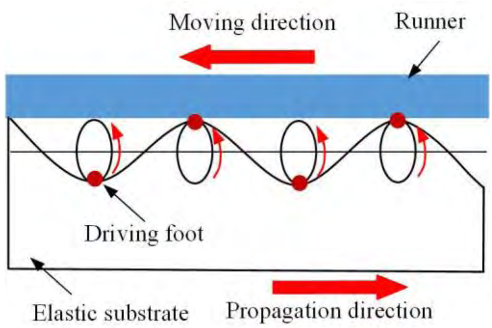

FIGURE 2. The traveling wave type actuation mode.

3) COMPOUND VIBRATION MODE TYPE

For a compound vibration mode type piezoelectric actuator, two separated vibration modes with the same frequency on the elastic substrate are generated with certain temporal shift. Generally, one vibration mode is used to control the positive pressure between the driving foot and the runner, the other vibration mode is used to drive the runner [53]–[57]. The vibration modes used in previous compound vibration mode type piezoelectric actuators mainly include the longitudinal, torsional and bending ones. As shown in Fig. 3, the longitudinal and torsional vibrations are excited, the former is used to adjust the positive pressure, while the latter is used to drive the runner, and the rotary motion can be achieved. There are a lot of different designs for the compound vibration mode type piezoelectric actuators, some of them are rotary, some are linear and some are multi-DOF. The compound vibration mode type piezoelectric actuators have merits of various structures, large force/torque and high power, but they require strict structure dimensions to ensure the two separated vibration modes have very close resonance frequencies. It should be noted that the actuators using two bending modes [58]–[61] can satisfy two identical frequencies easily by using a symmetrical cross-section, this merit makes the bending hybrid piezoelectric actuator very popular and useful.

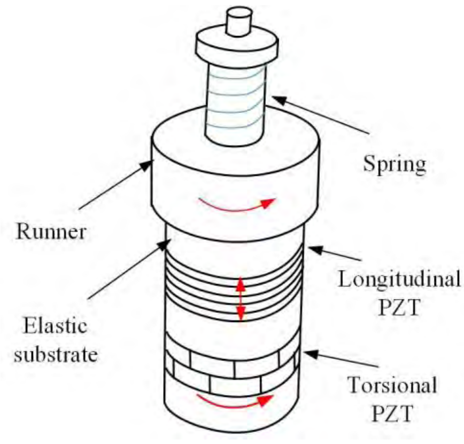

FIGURE 3. The compound vibration type actuation mode (longitudinal-torsional) [54].

B. INERTIAL ACTUATION MODE

The inertial actuation mode [62]–[65] is based on the inertia principle, which uses the fast response characteristic of piezoelectric material. An operating cycle consists of two steps, as shown in Fig. 4.

(1) A slow rising voltage excitation signal is used to excite PZT element of the stator, and it moves slowly. The runner is driven to follow the stator due to friction force, and moves slowly.

(2) A fast decreasing voltage excitation signal is applied to stator, which moves quickly, and returns to the initial stage. The runner keeps still because of the inertia.

As a result, the runner can be moved step-by-step when periodic excitation signal is applied to the PZT element. The actuators using the inertial actuation mode are usually simple and small in structure; their excitation signals are very simple, one-DOF motion requires only one signal. But their output forces are usually quite small, and rollback motions commonly exist.

C. CLAMPING AND FEEDING ACTUATION MODE

The clamping and feeding actuation mode [66]–[69] is inspirited by the biological motions, multiple groups of piezoelectric units are used to performance the "clamping" and "feeding" actions, and drive the runner alternately to achieve the actuation aim. There are mainly two types of clamping and feeding actuation modes: inchworm type and walking type. The former is inspirited by the motions of inchworms, while the latter is inspirited by the walking motions of animals. The operating processes of them are similar, one cycle is usually divided into six steps. Fig. 5 shows the operating details of an inchworm type actuator, the two groups of clamping units can clamp the guide alternately, while the actuation unit could finish the feeding motion. Fig. 6 gives a brief sketch of the walking type, the longitudinal PZT is used for the clamping action, while the shear PZT is used for the feeding motion, the actuator operates like walking, and drives the runner to move step-by-step.

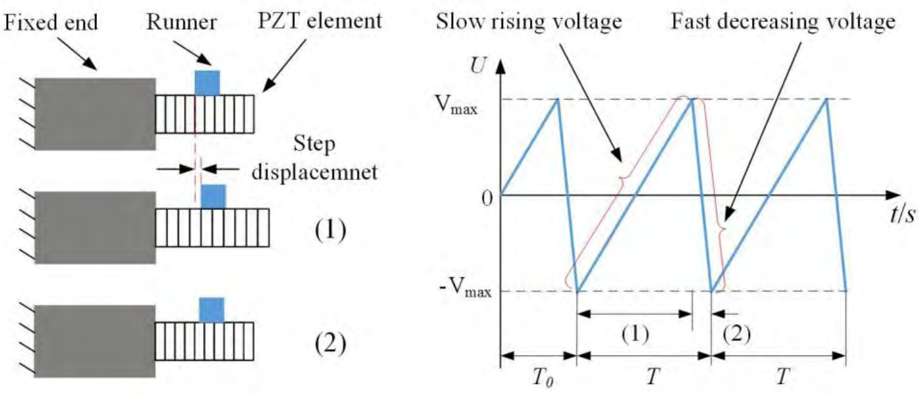

FIGURE 4. The inertial actuation mode.

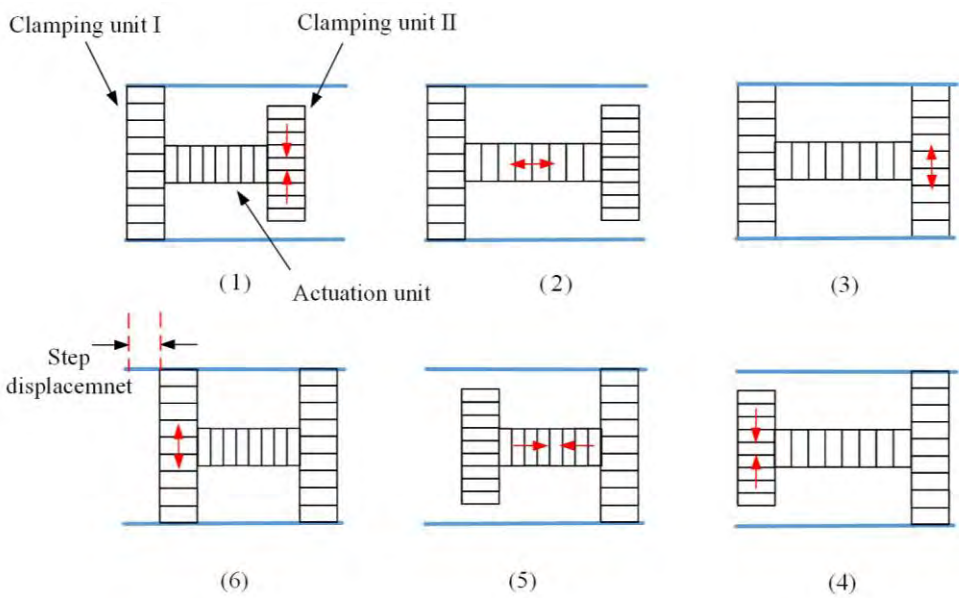

FIGURE 5. The inchworm type actuation mode [66].

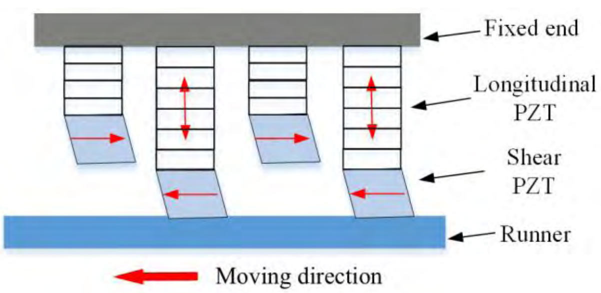

FIGURE 6. The walking type actuation mod e proposed by PI [32].

The actuators using the clamping and feeding actuation mode have long strokes and high resolutions, but the structures and excitation signals are complex due to the multiple groups of piezoelectric units.

D. DIRECT ACTUATION MODE

The operating principle of the direct actuation mode is simple, actuation unit drives the compliant mechanism connected with the execution unit directly, and the output motion is obtained. As shown in Fig. 7, the actuation unit extends when positive voltage signal is applied to it, the execution unit moves, and the output displacement is the extension multiplied by the amplification ratio of the compliant mechanism. Nanometer resolutions can be achieved easily by the actuators operating in direct actuation mode. But the strokes are short due to limited deformations of the PZT stacks

III. MULTI-ACTUATOR TYPE PIEZOELECTRIC STAGE

The structure of the multi-actuator type stage mainly includes the series and parallel types, and some series-parallel stages are also proposed for specific requirements.

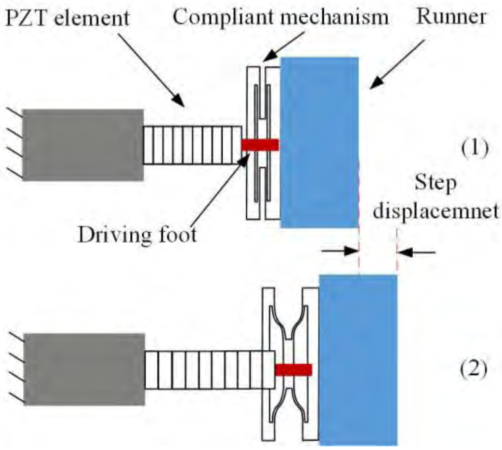

FIGURE 7. The direct actuation mode.

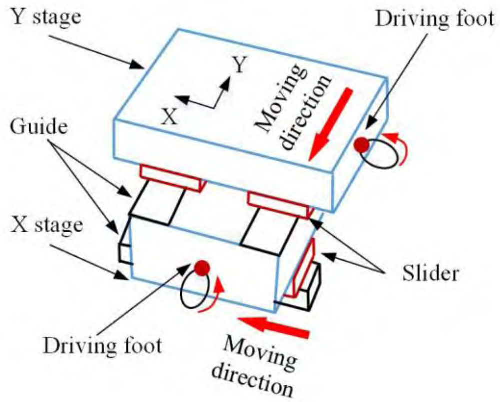

FIGURE 8. The series type stage.

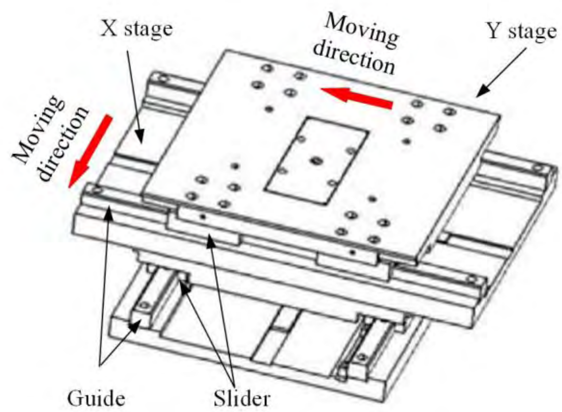

FIGURE 9. The XY series stage operating in resonance actuation mode proposed by Shi *et al.* [70].

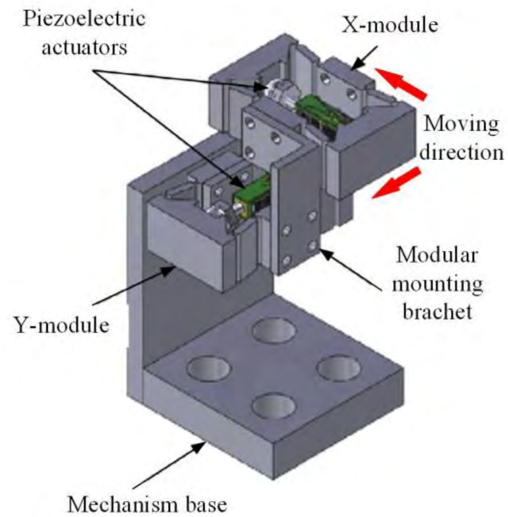

FIGURE 10. The series stage operating in direct actuation mode proposed by Pinskier *et al.* [73].

A. SERIES TYPE

The series type piezoelectric stage is based on the thought of modularization. As shown in Fig. 8, the input end of one single-DOF stage is connected to the output end of the other stage in series. The multi-DOF outputs can be obtained by combining multiple single-DOF stages in series.

In the literature, the XY series stage is studied widely. Shi *et al.* [70] proposed an XY series stage using the resonance actuation mode, as shown in Fig. 9, two linear piezoelectric actuators were adopted to achieve the two-DOF motions, large travel range was obtained with resolution of 1 μm. Kang *et al.* [71] presented an XY stage composed of two orthogonal groups of shear PZT stacks, the stage operated in the clamping and feeding actuation mode, a speed of 0.5 mm/s was achieved with a resolution of 10 nm in one-DOF. Pinskier *et al.* [72] designed a single-DOF flexure-based mechanism for two-DOF series stage [73], as shown in Fig. 10, the direct actuation mode was adopted, and the work space was $39.1 \times 42.1\ \mu m^2$. Lee *et al.* [74] also proposed an XY stage using the direct actuation mode, which achieved a travel range of $80 \times 80\ \mu m^2$ and resolution of 50 nm. Then a compact two-DOF stage based on "Z" shaped compliant mechanism [75] was developed, the stage also operated in the direct actuation mode, and the travel range was 17.65 μm and 15.45 μm in XY plane. In [76], an XY stage based on the direct actuation mode was designed, triangle amplifier mechanism was used, and the travel range reached to 41.6 μm and 42.9 μm in X and Y. Liu *et al.* [25] presented an XY series stage operating in the walking type actuation mode, as shown in Fig. 11, two longitudinal-bending hybrid piezoelectric actuators were used to drive the mobile stage, a large travel range was achieved, and the resolutions of 0.1 μm and 0.2 μm in X and Y directions were obtained.

The rotary-linear series stage is also proposed in some research. Hua *et al.* [77] designed a two-DOF stage using the inchworm type actuation mode, rotary-linear motions were achieved with angle and displacement resolutions of 0.3 μrad and 0.019 μm, the stroke was about 20 mm. In [78], a $Z\theta$ series stage operating in the inchworm type actuation mode was also developed, eight groups of piezoelectric stacks

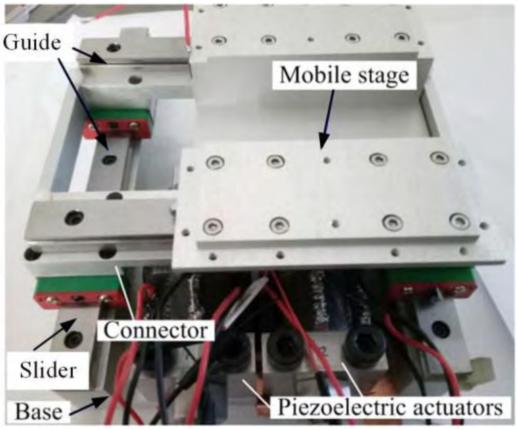

FIGURE 11. The XY series stage operating in walking type actuation mode proposed by Liu *et al.* [25].

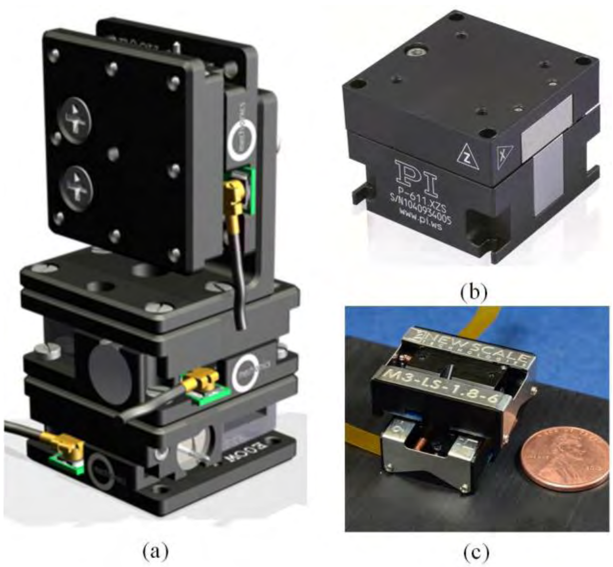

FIGURE 12. The commercialized series stage: (a) XYZ stage operating in inertial actuation mode produced by mechOnics, (b) XZ stage operating in direct actuation mode produced by PI, (c) XY stage produced by New Scale Technology.

connecting with several compliant mechanism were used, the maximum linear and rotary velocities were 105.31 μm/s and 3521.70 μrad/s, respectively.

Some series type piezoelectric stages have been commercialized. The company of mechOnics produced a number of series stages, in which the XYZ series type stage (MS15 xyz-mounted) operating in inertial actuation mode achieved 3.5 mm travel in X, Y and Z directions, the vertical and lateral deviations were 1 μm and 2 μm, respectively. The P-611 type XZ series stage produced by PI operating in the direct actuation mode with cross section dimensions of 44 $\times$ 44 mm^2, which achieved a travel range of 120 $\times$ 120 μm^2 with resolution of 0.2 nm. New Scale Technology also provided an XY series stage with compact structure, the controller was placed on the stage, the M3-LS series stage can achieve millimeter travel range with nanometer accuracy, in which the M3-LS-3.4-15 stage could operate in a range of 15 $\times$ 15 mm^2. Besides, some companies also produced single-DOF stage for assembling multi-DOF series stage, e.g., Cedrat Technologies, Nanomotion.

The performances of some series stages are presented in Table 1, stages with different actuation modes have different characteristics. This table provides a reference for choosing stages with specific requirements.

B. PARALLEL TYPE

Multiple piezoelectric actuators drive the compliant mechanism connected with the execution unit. As shown in Fig. 13, the output ends are connected to the execution unit together in parallel, multi-DOF outputs can be obtained.

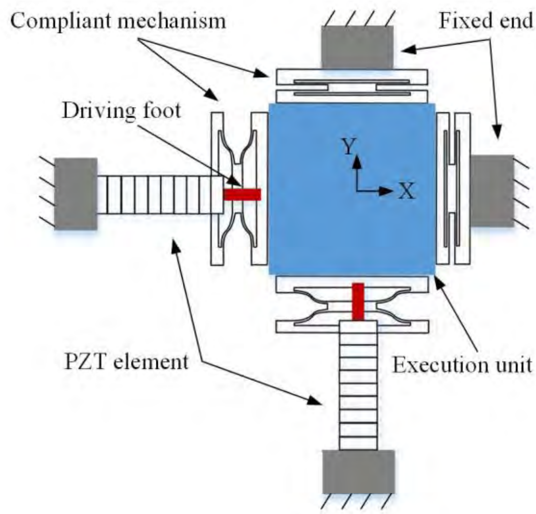

FIGURE 13. The parallel type stage.

Research on the parallel piezoelectric stage mainly focused on that operating in the direct actuation mode. The main demands in the industry are the XYZ stage, XY stage and XYθ stage. Whereas, some other stages with different output forms were presented for specific applications. For example, Clark *et al.* [79] designed an Xθ stage, as shown in Fig. 14, two groups of PZT elements were used to drive the compliant mechanism directly connected with the output platform, a travel range of 10.31 μm in X direction and 535.8 μrad in θ direction were obtained. In [80], a Z$\theta_X\theta_Y$ stage was developed, which was used for the implementation of a tip-tilt-piston motion. Yun and Li [81] proposed a six-DOF stage with compliant mechanisms for high precision positioning, the travel range was about 140 $\times$ 140 $\times$ 135 μm^3. Wu *et al.* [82] designed a six-DOF stage using a 6-prismatic-sphericalspherical parallel linked compliant mechanism driven by six piezoelectric actuators, as shown in Fig. 15, travel range of 8 μm with resolution of 5 nm and rotation range of 200 μrad with resolution of 0.7 μrad were obtained. Also, a six-DOF stage with similar structure was

TABLE 1. Performances of series stage.

Reference	Year	DOF	Actuation mode	Size (mm)	Speed (μm/s)	Resolution (nm)	Range (mm)
Shi et al. [70]	2008	XY	Compound vibration mode	200 × 200 × 97	1.9×10^5	1000	Unlimited
Kang et al. [71]	2008	XY	Walking actuation mode	96 × 96 × 39	500	10	Unlimited
Hua et al. [77]	2014	Xθ	Inchworm actuation mode	100 × 32 × 50	482 and 0.01 rad/s	19 and 0.3 μrad	20 and unlimited
Pinskier et al. [73]	2016	XY	Direct actuation mode	82 × 50 × N/A	N/A	N/A	0.039 × 0.042
Lee et al. [74]	2016	XY	Direct actuation mode	N/A	N/A	50	0.080 × 0.080
Li et al. [75]	2017	XY	Direct actuation mode	130 × 150 × 8	N/A	N/A	0.017 × 0.015
Liu et al. [25]	2018	XY	Walking actuation mode	40 × 112.8 × 38	101.7 and 124.2	100 and 200	Unlimited
MS15 xyz [33]	N/A	XYZ	Inertial actuation mode	15 ×7 × 15	1.5×10^3	N/A	3.5 × 3.5 × 3.5

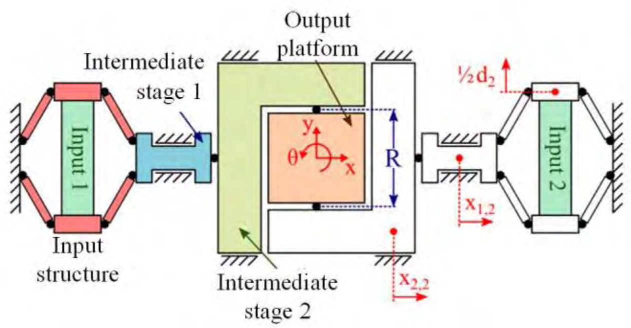

FIGURE 14. The X θ parallel type stage proposed by Clark *et al.* [79].

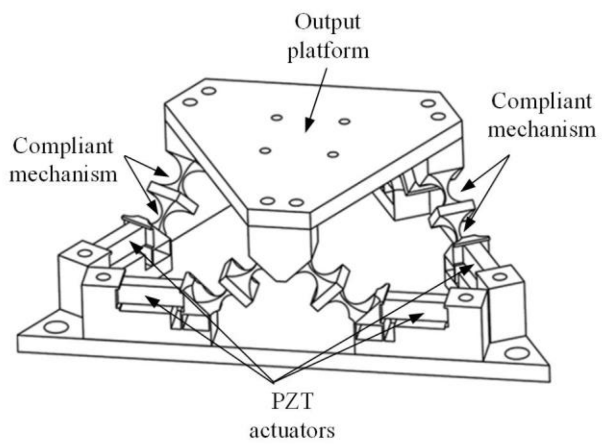

FIGURE 15. The six-DOF parallel type stage proposed by Wu *et al.* [82].

proposed by Du *et al.* [14], which was used for high-precision pointing mechanism.

For the XYZ stage, Li and Xu [83] designed an XYZ stage shown in Fig. 16, which achieved a workspace of $165.8 \times 5.4 \times 6.5\ \mu m^3$ with resolution of 180 nm. In [23], an XYZ stage with high speed was proposed, the FEA

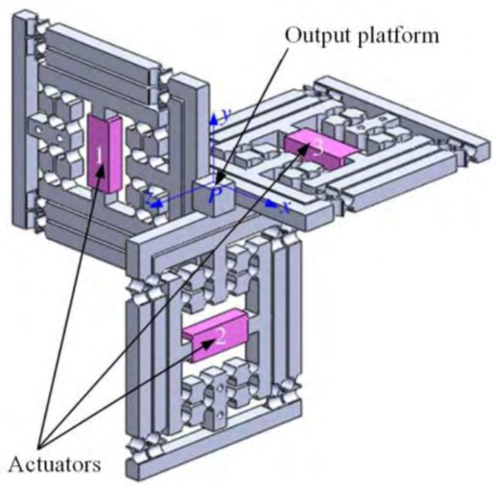

FIGURE 16. The XYZ parallel type stage proposed by Li and Xu [83].

results revealed that the workspace of the stage was about $9.2 \times 9.2 \times 3.1\ \mu m^3$. Zhu *et al.* [84] proposed an XYZ stage for nanocutting, the obtained workspace was about $12.37 \times 13.14 \times 11.72\ \mu m^3$. In addition, some designs [85], [86] of the XYZ stage were proposed without prototypes.

Since there are a lot of research about the XY and XYθ parallel stages [87]–[92] in the literatures, some of them are listed in Table 2, where the performances of different parallel stages are presented. Li and Xu [93] developed an XY planar stage composed of two groups of PZT stacks, the stage operated in the direct actuation mode, a travel range of $180 \times 180\ \mu m^2$ and resolution of 1.5 nm were achieved in theory. The XYθ stage was usually composed of three kinematic chains in parallel, and the RRR or PRR chains were used mostly in the designs [94]–[96]. Chang *et al.* [97] developed an XYθ stage operating in the direct actuation mode, the related analyses were performed. Wang and Zhang [98]–[100] presented an XYθ stage actuated by three piezoelectric actuators combined

TABLE 2. **Performances of parallel stage.**

Reference	Year	DOF	Actuation mode	Size (mm)	Resolution (nm)	Range (μm)
Clark et al. [79]	2015	Xθ	Direct actuation mode	N/A	23.3 and 1.04 μrad	10.31 and 535.8 μrad
Wu et al. [82]	2008	Six-DOF	Direct actuation mode	15 × 15 × 15 cm^3	5 nm and 0.7 μrad	8 and 200 μrad
Li et al. [83]	2011	XYZ	Direct actuation mode	About 105 × 105 × 105	N/A	165.8 × 5.4 × 6.5
Gao et al. [101]	1999	XY	Direct actuation mode	N/A	20 and 18	45 × 40
Yao et al. [102]	2006	XY	Direct actuation mode	N/A	20	87 × 87
Li et al. [103]	2009	XY	Direct actuation mode	220 × 220 × N/A	N/A	117 × 117
Yong et al. [104]	2009	XY	Direct actuation mode	10 × 10 × 18	N/A	25 × 25
Li et al. [105]	2011	XY	Direct actuation mode	116 × 116 × 46	220	132 × 126
Lai et al. [22]	2012	XY	Direct actuation mode	269× 269 × N/A	3	41 × 41
Qin et al. [106]	2013	XY	Direct actuation mode	230 × 230 × 20	±40 (tracking errors)	8 × 8
Du et al. [107]	2016	XY	Direct actuation mode	190× 190 × 10	3	19.53 × 19.07
Zhang et al. [108]	2017	XY	Direct actuation mode	68.5× 61 × 68.5	20	127 × 127
Mukhopadhyay et al. [109]	2008	XYθ	Direct actuation mode	15 × 15×N/A	1000	18 × 18 and 1.72°
Dong et al. [110]	2016	XYθ	Direct actuation mode	N/A	N/A	39.18 × 39.26× 2.01 mrad
Wang et al. [98]	2016	XYθ	Direct actuation mode	N/A	5.5, 5.9 and 1.0 μrad	283.13 × 284.78 × 8.73 mrad
Cai et al. [111]	2017	XYθ	Direct actuation mod	150 in diameter × 18	153.6 and 106.9 (tracking errors in X and Y)	6.9 × 8.6 × 2891 μrad
Deng et al. [112]	2018	XYθ	Compound vibration mode	220 × 220 × 55	N/A	Unlimited
Morita et al. [113]	2002	XYθ	Inertial actuation mode	160 × 160×N/A	18.6 × 10^3 (average deviation)	Circle 3.0 mm in diameter
Yan et al. [114]	2006	XYθ	Walking actuation mode	5 × 5 × 20	N/A	Unlimited

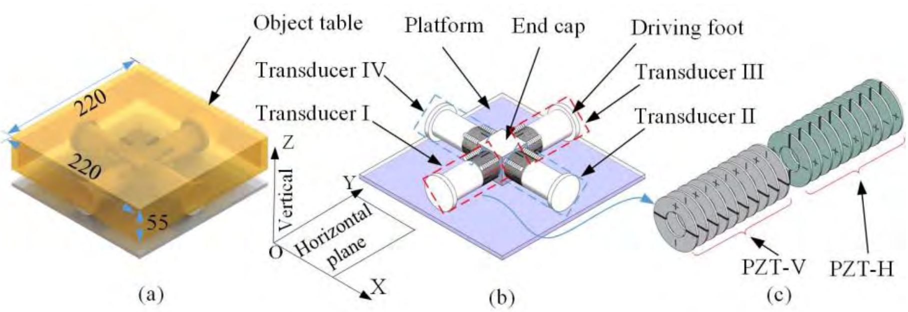

FIGURE 17. **The bending-bending compound vibration mode type XY θ parallel stage proposed by Deng *et al.* [112] (unit: mm).**

with three two-level lever amplifiers, the structure optimization, modeling, and controlling were performed, and it could achieve a workspace of 283.13 μm × 284.78μm × 8.73 mrad with high-accuracy positioning.

Furthermore, some parallel stages operating in the resonance, inertial or clamping and feeding actuation modes [115]–[121] were presented. Deng *et al.* [112] proposed an planar stage composed of four bending-bending hybrid sandwich transducers in parallel, as shown in Fig. 17, the planar motions could be obtained by the coordination of the four transducers, the maximum linear and rotary speeds of 19.8 mm/s and 0.266 rad/s were obtained when operating at bending-bending compound vibration mode. Morita *et al.* [113] designed an XYθ stage utilizing the inertial actuation mode, as shown in Fig. 18, three groups of inertial type actuators were connected to the execution unit together in parallel, a circle 3.0 mm in diameter was drawn and the average deviation was 18.6 μm. In [114], a planar stage operating in the clamping and feeding actuation mode was presented, the XYθ outputs were achieved through the forces between the four legs and the worktop.

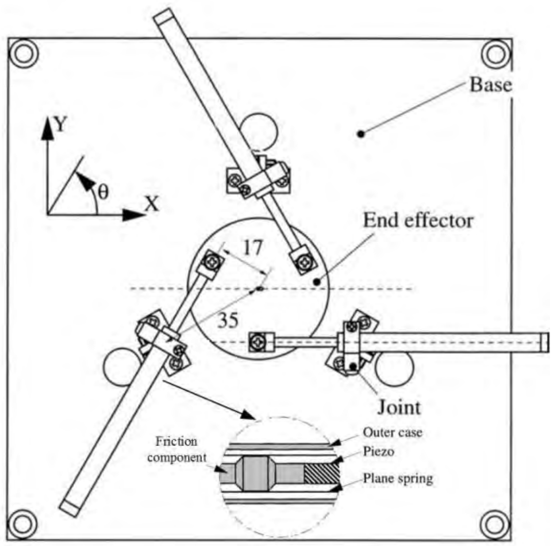

FIGURE 18. The inertial XY θ parallel stage proposed by Morita *et al.* [113].

Furthermore, some parallel stages are commercially available from a number of companies including the PI, Thorlabs, Newport, Piezo Electric Technology, etc.

C. SERIES-PARALLEL TYPE

The series-parallel type stage combines the series and parallel structures to achieve multi-DOF outputs.

The series-parallel XYZ stage connects the parallel type XY stage and the Z stage in series, and the characteristics are studied by many scholars. Ku *et al.* [122] presented an XYZ stage with resolution of 1 nm. Kim *et al.* [123] designed an XYZ stage for atomic force microscopy scanner with similar structure, the full range was 100 × 100 × 10 μ m^3. Kenton and Leang [124], [125] designed an XY-Z stage, as shown in Fig. 19, the travel range of the prototype was approximately 9 × 9 × 1 μm^3, respectively. In [126], an X-YZ stage with a travel range of 6.34 × 6.59 × 10.13 μm^3 and tracking error of 30 nm was presented. Tang *et al.* [127] developed a X-YZ stage shown in Fig. 20, a workspace of 10.39 × 15.43 × 15.55 μm^3 was achieved, which was used for elliptical micro/nano-positioning motion.

Some six-DOF stages using the series-parallel type structure were proposed in some research. Gao and Swe [128] developed a six-DOF stage using the series-parallel type structure, the displacement resolution could reach to 10 nm.

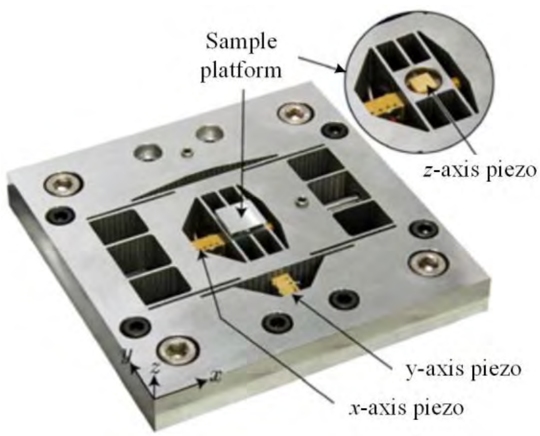

FIGURE 19. The series-parallel XY-Z stage proposed by Kenton *et al.* [125].

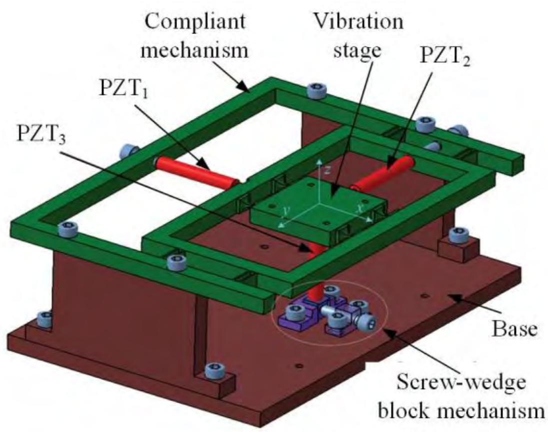

FIGURE 20. The series-parallel X-YZ stage proposed by Tang *et al.* [127].

Cai *et al.* [129] presented a six-DOF stage, an in-plane parallel XYθ_Z stage and an out-of-plane Z$\theta_X\theta_Y$ stage were connected in series, the travel range was 8.2 × 10.5 × 13.2 μm^3 in X, Y, Z directions with resolutions of 31 nm, 25 nm, and 7 nm, the rotation range was 107 × 100 × 225 μrad^3 around axes X, Y, and Z with resolutions of 20 nrad, 25 nrad and 0.8 nrad, respectively. In [130], a six-DOF stage based on bridge-type amplifier was proposed, the travel range was 111.38 × 111.38 × 260.06 μm^3, and the rotation range around axes X, Y, and Z was 4580 × 4580 × 2710 μrad^3.

IV. SINGLE-ACTUATOR TYPE PIEZOELECTRIC STAGE

The single-actuator type piezoelectric stage is driven by one multi-DOF piezoelectric actuator through friction force. The multi-DOF actuators operating at the resonance actuation mode are mostly studied. The multi-DOF outputs of the multi-DOF piezoelectric actuator are mainly obtained by the partitioning excitation method.

In the literature, Ferreira and Minotti [131] proposed an XY piezoelectric actuator using the resonance actuation mode, and standing waves could be excited on the surface of the elastic substrate by applying excitation signals to

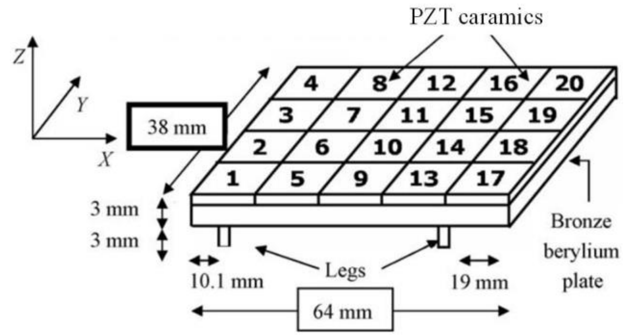

FIGURE 21. Standing wave type multi-DOF actuator proposed by Dembélé and Rochdi [132].

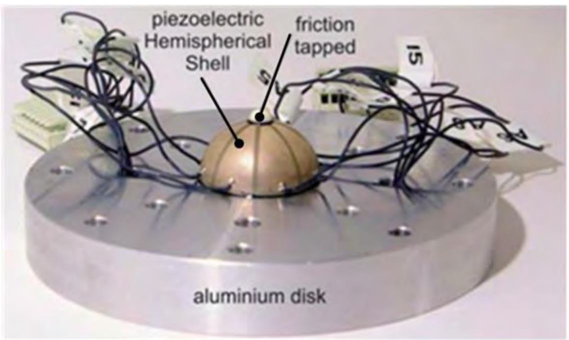

FIGURE 22. The small hemispherical multi-DOF actuator proposed by Bastian and Schinkoethe [137].

piezoelectric ceramics in specific areas, then oblique line trajectories on the driving feet were generated, and XY outputs were achieved, a positioning resolution less than 100 nm was achieved for an unlimited travel range with linear speeds between 1 mm/s and few cm/s. Dembélé and Rochdi [132] also proposed a standing wave type multi-DOF piezoelectric actuator with similar structure using 20 piezoelectric ceramics, as shown in Fig. 21, $XY\theta_Z$ motions were achieved by the friction forces between the four legs and the worktop. Li *et al.* [133] proposed a small XY piezoelectric actuator, 10 pieces of piezoelectric ceramics were used to excite the vibrations in a square elastic substrate and converted into the XY motions through the friction force. Hariri *et al.* [134], [135] proposed several patch type piezoelectric actuators, a traveling wave type planar actuator [136] that consisted of an aluminum plate structure with four non-collocated piezoelectric patches bonded on its surface was presented, a planar motion was achieved with the maximum speed of 133.3 mm/s at 60 V.

Multi-DOF actuators composed of piezoelectric ceramics without elastic substrate were proposed to obtain motion stage with small size. Bastian and Schinkoethe [137] developed a three-DOF actuator made of 8 piezoelectric hemispherical shell with radius of 12 mm and wall thickness of 2 mm, as shown in Fig. 22, a linear output speed of 400 mm/s was achieved under voltage of 120 V_{amp} and preload force of 20 N. Chen *et al.* [36] and Guo *et al.* [37] designed a variety of small multi-DOF actuators; as shown in Fig. 23(a), a small piezoelectric tube was used as a stator, the outer surface of the tube was divided into four zones, and three-DOF outputs were obtained by applying different exciting signals to the four zones, the outer diameter and length of the actuator were 5 mm and 15 mm; besides, a single piezoelectric single-crystal square-bar was utilized as the stator of the actuator shown in Fig. 23(b), the four sides of the stator were bonded with electrodes, and the longitudinal and bending vibrations can be excited by applying specific signals, XY outputs were obtained with driving force of 0.25 N and motion speed of 35 mm/s.

Some research developed multi-DOF actuators for high output speed. Mashimo and Toyama [138] developed an $X\theta$ piezoelectric actuator, as shown in Fig. 24, the stator was fabricated as a single metal cube with a through-hole, a piece of two-zone ceramics was attached to all four sides of the stator, the expansion and contraction modes of the stator could be excited by applying the related excitation signals, the inner circle of the hole contracted and expanded, and driven the output shaft to rotate or translate, a maximum linear speed of 63 mm/s was obtained, the structural optimization

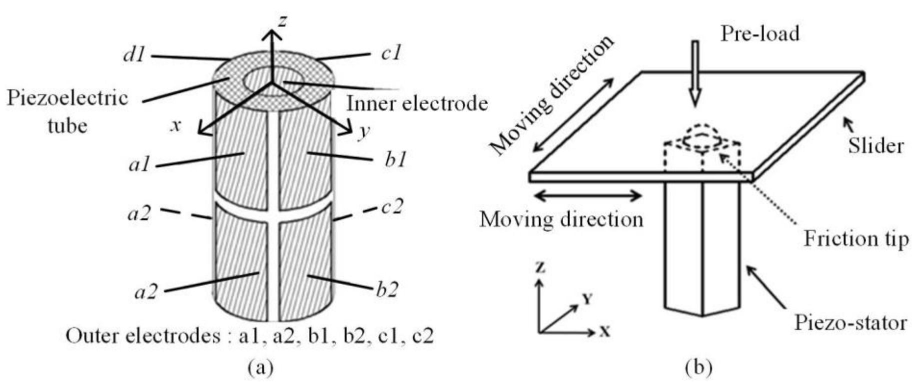

FIGURE 23. Small size piezoelectric actuator proposed by Dong, (a) the piezoelectric tube stator [37], (b) the piezoelectric square-bar stator [36].

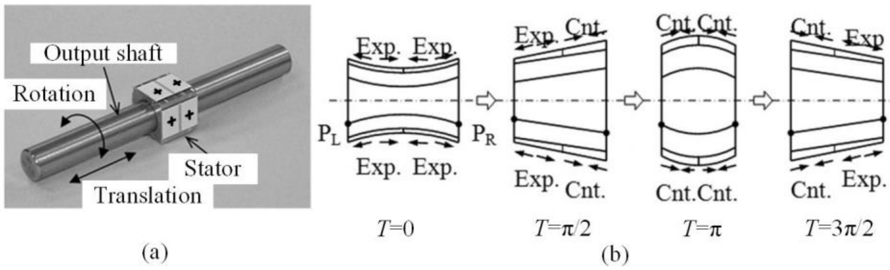

FIGURE 24. The X θ piezoelectric actuator proposed by Mashimo and Toyama [138].

and vibration analysis were developed [139], [140]. In [141], an Xθ piezoelectric actuator using 4 pieces of slanted piezoelectric ceramics was also presented, the longitudinal and torsional modes could be excited, and the translation and rotary outputs were achieved.

The designs adopted the sandwich structure were presented for large output force. Shi *et al.* [35] designed an XY planar actuator using four sandwich transducers, as shown in Fig. 25, the longitudinal and bending vibration modes were excited and elliptical trajectory on the driving foot was formed, the actuator could move in the worktop by the friction force, and the maximum speed of 960 mm/s and driving force of 103 N were achieved. Liu *et al.* [142] developed an XZ actuator using a longitudinal-bending hybrid sandwich transducer, the X motion was obtained by the second longitudinal and fifth bending vibration modes, while the Z motion was obtained by the two orthogonal fifth bending vibration modes, the maximum output forces along X and Z directions were tested to be 24 N and 22 N when the preload was 200 N. Yan *et al.* [143] proposed an XY planar actuator with sandwich structure, the second bending mode and first longitude mode were excited to form the elliptical trajectory of the driving tip, the operating principle was simulated by the finite element method.

Some multi-DOF actuators using the inertial or direct actuation modes were presented by researchers. Blackford and Jericho [144] and Blackford *et al.* [145] designed an XY stage using a piezoelectric tube that could bend in X and Y directions, the platform was moved step-by-step by the inertial actuation mode, and step displacement resolution could reach to 10 nm. In [146], an inertial XY stage composed of a piezoelectric tube with the same operating principle was presented. The multi-DOF actuators operating in the direct actuation mode were also proposed. Fleming *et al.* [147], [148] developed an XY stage composed of a sheet of piezoelectric material with a number of cuts designed to create parallel beams, as shown in Fig. 26, the central platform could be moved directly in a range of $8.6 \times 8.6\ \mu m^2$. Su *et al.* [149] presented an direct actuation type XYZ actuator with travel range of 9.18 μm, 9.06 μm and 1.55 μm in X, Y, Z directions.

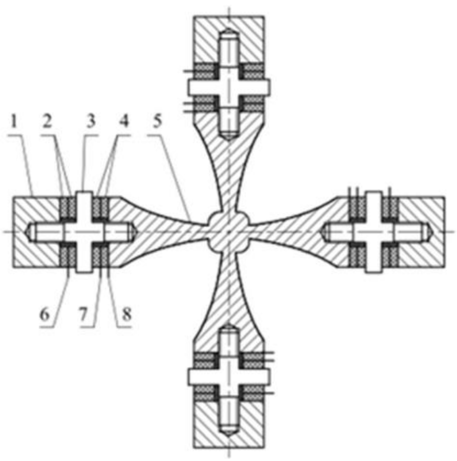

FIGURE 25. The XY planar actuator using sandwich structure proposed by Shi *et al.* [35].

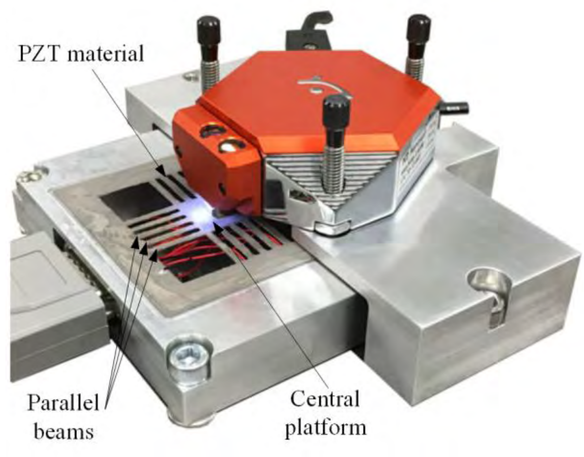

FIGURE 26. The XY stage operating in direct actuation mode proposed by Fleming *et al.* [148].

Table 3 shows the performances of some multi-DOF actuators. It can be seen that actuators using the resonance actuation mode are mostly researched, they operate with large output speeds and forces, but their resolutions are limited to micron scale. Actuators operating in others actuation modes are presented by several researchers, the resolutions can be

TABLE 3. Performances of multi-DOF actuator.

Reference	year	DOF	Actuation mode	Size (mm)	Resolution (nm)	Speed (mm/s)	Output (N)
Demb´el´ et al. [132]	2006	XY	Standing wave type	64 × 38 ×2.5	2.5×10^3	20	N/A
Chen et al. [36]	2014	XY	Compound vibration mod	2 × 2 × 9	N/A	35	0.25
Mashimo et al. [138]	2009	Xθ	Compound vibration mode	10 × 10 × 10	N/A	63 and 160 rpm	N/A
Shi et al. [35]	2009	XY	Compound vibration mode	98.9 × 98.9 × 34.6	N/A	960	103
Liu et al. [142]	2018	XY	Compound vibration mode	196 × 57 ×35	N/A	572 and 543	24 and 22
Blackford et al. [144]	1990	XY	Inertial actuation mode	13 × 11 × 37	50	0.1	N/A
Fleming et al. [148]	2017	XY	Direct actuation mode	72.3 × 72.3 × 0.508	N/A	N/A	N/A
Su et al [149]	2018	XY	Direct actuation mode	60 × 60 × 90	13	N/A	N/A

TABLE 4. Comparisons of different actuation modes for Multi-DOF motion stage.

Actuation mode	Driving force	Structure	Performances	Shortcomings	Suitable fields
Resonance actuation mode	Dynamic friction force	Moderate	Output speed: m/s Resolution: micrometer	Easy to generate heat, wear and tear, accuracy loss	Micron precision, large travel range
Inertial actuation mode	Static and dynamic friction force	Simple	Output speed: mm/s Resolution: sub-micrometer	Rollback, accuracy loss, small force	Micron precision, millimeter to meter travel range
Clamping and feeding actuation mode	Static friction force	Complex	Output speed: μm/s Resolution: sub-micrometer	Complex structure and excitation signals	Sub-micron precision, micrometer to millimeter travel range
Direct actuation mode	Axial force or static friction force	Moderate	Output speed: fast Resolution: nanometer	Limited travel range	Nanometer precision, micrometer travel range

improved, but the outputs are limited. Thus, actuators operating with large output speeds and nanometer resolutions should be investigated in the future.

V. DISCUSSION

It can be found from the above sections that the multi-DOF piezoelectric motion stages can operate in different actuation modes with different structures, and have different output performances. The parallel multi-actuator stages have characteristics of compact structure, easy realization of high accuracy, but their travel ranges are limited in an range of dozens to hundreds of micrometers. The series multi-actuator stages can solve this problem, one actuator is responsible for one-DOF, and large travel range can be obtained by the stepping motions through actuation modes of resonance, inertial or clamping and feeding. However, the coupling vibrations among different DOF superposes with each other, leading to accuracy loss. The single-actuator type stage using one multi-DOF piezoelectric actuator to move the output platform through the friction force. Similarly, the actuators operate with large output speeds and forces when using the resonance actuation mode, but the resolutions are limited. The resolutions can be improved by utilizing the direct actuation mode, however, the travel range is not large enough. It is the actuation modes that determine the output characteristic of the stage utilizing multi-DOF actuator. The output performances of the stage under different actuation modes are given in Table 4, and each driving mode has its own application scopes. Thus, it can be concluded that large travel range and high resolution of the developed stage cannot be achieved simultaneously. The reasons are diverse, but they are mainly determined by the structures and actuation modes. The characteristics of the parallel and series structures have been discussed above, and the reasons for different actuation modes will be discussed as follows.

The direct actuation mode usually uses the extension of the PZT stacks, but the travelling range is limited because the deformations of the PZT stacks are only 0.1% of their lengths, a compact structure requires that the size of the PZT stack should not be too large. The motion stage can obtain a large travel range through stepper motions, which can be realized by means of resonance, inertial or clamping and feeding actuation modes through friction forces, but the operating principles and the nonlinearity of the piezoelectric materials in low voltage limit the displacement resolutions of the stages. Besides, the cross coupling among different DOF and wear problems also effect the accuracy. Some methods are proposed to alleviate these problems, which are the state of arts of the multi-DOF piezoelectric motion stages.

A. NOVEL STRUCTURE

The piezoelectric multi-DOF motion stage can use different structures to satisfy different requirements due to the characteristic of flexible structure.

1) COMPLIANT AMPLIFICATION MECHNASIM

The travel range of the direct type stage is limited, so novel compliant amplification mechanisms for the parallel stages are proposed by some researchers. Wang and Zhang [98] presented a planar stage using two-level lever compliant amplification mechanism, the amplifications of the first-level and second-level levers were 4.82 and 1.9, a travel range of 283.13 μm × 284.78 μm × 8.73 mrad was obtained. Gao *et al.* [86] proposed a modified differential lever displacement amplifier with displacement amplification ratio of 7.1. In 2018, Wu and Xu [42] gave a survey on recent designs of the micro-/nano-positioning stages, where the compliant amplification mechanism was summarized.

2) DECOUPLED COMPLIANT MECHNASIM

The cross coupling problems are unavoidable for the multi-DOF piezoelectric motion stage system, but a suitable structure can greatly reduce the impact of cross coupling on the system. Li and Xu [83], [105] designed several piezoelectric XY stages with decoupled structure, in which the double compound parallelogram flexures with large transverse stiffness and two-dimensional compound parallelogram flexures were proposed, and they were constructed at the input and output ends of the stage, the effectiveness of the proposed mechanism was confirmed by the experiment results. Zhu *et al.* [92] developed a leaf-type double parallelogram compliant mechanism, which was also adopted at both input and output ends of the stage, the lateral stiffness and dynamic characteristics were significantly improved, an excellent decoupling performance was obtained with the output coupling below 1%.

3) MULTI-LEGS BIONIC STAGE

Inspired by the flexible use of multiple motion modes by multi-leg animals in nature, the multi-leg stages based on the principle of bionics were proposed. The multi-DOF outputs could be achieved through the coordination of the multiple legs, and the large travel range and high resolution can be realized in different actuation modes, respectively. Deng *et al.* [112] proposed a four-legs piezoelectric stage, the planar motions were achieved through the coordination of the four legs, the stage operated at the resonance mode, and run at the worktop like an animal to obtain a large travel range, besides, the stage could operate at the direct actuation mode, the contacting points between the legs and the worktop kept still, the stage swung, and a displacement resolution of 16 nm was obtained.

B. MODELING AND CONTROL

Modeling and controlling approaches of the multi-DOF piezoelectric motion stage systems are studied to obtain a stage with high precision, fast response and good reliability, which is necessary for its large-scale application in precision fields. The inherent creep and hysteresis of piezoelectric materials cause the nonlinearities problems, which bring difficulty to modeling for the stage system. Thus, different creep and hysteresis modeling approaches are proposed by a number of researchers. Moreover, the stage operated in the resonance, inertial, or clamping and feeding actuation modes utilize the friction force to achieve the stepping motions, but the friction with hysteresis that affects the reliability of the stage is undesired, modeling of the friction contact and compensating the hysteresis are necessary. In addition, the heating problem also affects the reliability of the stage as the physical and material properties change with the rising of temperature, the wear and tear problems also occur at the driving tips of the resonance and inertial actuation mode type stages when heat cannot be dispersed in time, which leads to accuracy loss.

1) MODELING AND CONTROL OF THE CREEP AND HYSTERIESIS NONLINEARITIES

Various techniques have been reported to model and control the creep and hysteresis nonlinearities [150]–[158] in recent years. The developed models are used to represent the system behaviors in term of the creep, hysteresis, and the controllers are used to compensate the nonlinearities. The related progresses of different modeling and control methods were discussed and summarized by the survey of Gu *et al.* [159] in 2016, and the emerging research problems were summarized and put forward.

2) MODELING OF THE FRICTION CONTACT

The contact model between the multi-DOF piezoelectric actuator and execution unit are proposed by some scholars for the stage using friction forces. As we all know that the friction is difficult to model and simulate, thus, various of friction models are developed in different conditions. The traditional friction contact modeling includes the "Coulomb friction model", "LuGre model", "Elastoplastic friction model", and "Dahl friction model". Liu *et al.* [160] presented a review of these friction models applied to inertia motion systems in 2015, they also [161] designed and finished experiments on the same test-bed of the inertial motion system to compare the accuracy of five friction models, experimental results showed that the "LuGre model" had the best accuracy. Ryou and Oldham [162] discussed the contact interaction of multi-legs piezoelectric structures, which captured various dynamic features. Qu *et al.* [163] also presented a contact model for the multi-legs piezoelectric robot, which agreed well with the experimental results.

3) TEMPRATURE CHARACTERISTIC EVALUATION

The temperature characteristics of the piezoelectric mechanisms were investigated in the literature. Weaver *et al.* [164] presented an overview of measurement techniques adopted for high temperature measurements. Chen *et al.* [165] developed a theoretical model to research the effect of ambient temperature on the characteristics of piezoelectric mechanism, and experimental results revealed that the resonant frequency of the piezoelectric structure and the output performance decreased as the temperature increased. Li *et al.* [166] investigated the thermal-mechanical-electric coupling dynamics of a standing wave ultrasonic type actuator, experimental results showed that the temperature increased faster and reached a higher final steady temperature when the actuator operated under a higher driving voltage or a driving frequency closer to the resonance frequency. Liu *et al.* [167] also studied the thermal characteristics of bending hybrid piezoelectric actuators under different exciting methods.

C. ACTUATION MODE

Some methods have been presented to improve the actuation modes, and the output performances of the piezoelectric stage have been improved.

1) IMPROVEMENT OF ACTUATION MODE

The resonance actuation type structures always suffer from the heat and wear problems, Liu *et al.* [168] presented a method by applying intermittent signals operating at resonance frequency to achieve stepping motion, the step displacement resolution was 0.21 μm, the heating problems can be alleviated by the intermittent excitation method. Xu *et al.* [169] proposed an actuation mode using the oblique line trajectory, which can be seen as a standing wave type actuation mode operating in nonresonant frequency, it was helpful to solve the heat problem.

The inertial actuation mode was also improved by some scholars. The ultrasonic friction reduction method was used to reduce the rollback phenomenon at the slip stage and improved the performance. Cheng *et al.* [170] used the ultrasonic friction reduction method on inertial mechanism, the velocity and load characteristics were increased. The rollback motion was restrained by Wang *et al.* [171] through that method. And the step efficiency was greatly improved from 36.9% to 91.2% [172]. Then, Li *et al.* [173] proposed an excitation signal with symmetrical hybrid driving waveform for the inertial mechanism based on the ultrasonic friction reduction, the step efficiencies can reach up to 90%. Several attempts were also made to increase the operating frequency of the inertial mechanism up to its resonance, which could improve the output performances. Ma *et al.* [174] proposed a resonant type inertial actuator with rectangular pulse excitation signals at uneven duty ratio, the maximum efficiency reached to 2.1%, which was higher than that of the previously reported designs. Besides, Morita *et al.* [175], Nishimura *et al.* [176], and Yokose *et al.* [177] developed a method combining two resonant frequency modes to achieve the same output at low voltage, the frequency ratio was designed as 1:2, and the heat generation problem was significantly reduced because dielectric losses were suppressed under the low input voltage operation. Pan *et al.* [178] also utilized the similar method to actuate a piezoelectric bending actuator. In 2018, Yokozawa *et al.* [179] used the method for a lead-free piezoelectric actuator, a driving speed of 53 mm/s was achieved under no-load condition at the voltage of 6 V_{p-p}, a good output was achieved, and it was environmentally friendly.

2) COMBINING DIFFERENT ACTUATION MODES

Combining different actuation modes is an effective method to achieve a large travel range and a high resolution. Large travel range can be obtained by the stepping motion of the stage when operating at the resonance, inertial or clamping and feeding actuation modes, and the high resolution can be achieve through the direct actuation mode. Xu *et al.* [180] proposed a piezoelectric actuator that used the method of combining actuation modes, the maximum output speed of 1750 mm/s was obtained by the actuator at the resonance actuation mode, and minimum output displacement of 50 nm was achieved at the direct actuation mode. Li *et al.* [181] developed initial type actuator, which achieved maximum speed of 7.95 mm/s at the initial actuation mode and positioning error of 10 nm at the direct actuation mode. Deng *et al.* [112], [182] proposed a planar stage that could operate at the resonance, walking and direct actuation modes, the maximum linear and rotary speeds of 19.8 mm/s and 0.266 rad/s were obtained at the resonance mode, linear and rotary displacement resolutions of 16 nm and 0.198 μrad were achieved at the direct actuation mode.

VI. CONCLUSION AND OUTLOOK

Multi-DOF piezoelectric motion stage is becoming more and more promising with the development of nanotechnology, including the related measurements, materials, mechanics, and manufacturing technologies. The multi-DOF piezoelectric motion stage has advantages of easy realization of nanometer resolution, self-locking at power-off state, flexible structure, fast response speed, diversified actuation modes and immunity from electromagnetic radiation. These characteristics allow it to be applied in a series of fields that require high accuracy and specific working conditions. This study gives a critical review of the multi-DOF piezoelectric motion stage, mainly including the actuation modes and structures. The characteristics of the multi-actuator type stage including the series and parallel type stages, and the single-actuator type stage mainly including the multi-DOF actuator, are discussed. The series stage has flexible structure and actuation mode, it is easy to realize a large travel range, but the cross coupling exists in motion of each DOF and superposes with each other, the accuracy cannot be guaranteed in large travel range. The parallel stage has merits of compact structure and high accuracy, and it is studied mostly, but the travelling range is limited. The single-actuator type motion stage uses the multi-DOF actuator to obtain multi-DOF outputs with compact structure, but the performances are determined by the actuation modes, and the performances of the motion stage using different actuation modes are compared, the characteristics and application fields are discussed and summarized, the previsions research mainly focuses on the resonance type multi-DOF actuators, which operate with large output speeds and forces, but the resolutions are limited. Although multi-DOF actuators operating in others actuation modes obtain improved resolutions, the outputs are limited. As a concluding remark: the high accuracy and large travel range of the developed stage cannot be achieved simultaneously.

The state of arts of the research to the stage are briefly summarized, including the novel structure, modeling and controlling, and actuation modes. And the future research directions are suggested as follows:

(1) Repeatability and reliability research for the stage. It is known that the properties of piezoelectric materials are greatly influenced by temperature, the temperature changes when the stage works for a long time, the output performances will change and affect the reliability of the stage. Besides, the wear problems of the stage using dynamic friction force also affect the repeatability and reliability. Thus, the wear-resistant material or friction reduction technology should be investigated to avoid the wear problems. As a result, the repeatability and reliability of the stage should be studied by more theories and experiments, and the relevant results should be evaluated, which is the basis for the large-scale industrial applications of the stage.

(2) Designing novel structure. The basic requirements for the structure of the stage is compact, simple, and high rigidity. A compact structure is conducive to the application in precision fields. A simple stage is easy to model and control. The high rigidity characteristic can ensure the good dynamic characteristics and anti-interference capability, which is necessary for the stability for a stage system.

(3) Modeling and controlling for the stage. The cross coupling, creep and hysteresis nonlinearity, heat and wear problems make modeling for the stage a challenge. Research on suitable modeling approaches for solving these problems is essential, and the related controller should be designed to compensate the nonlinearity, and ensures the reliable of the whole system. In addition, the method combining different actuation modes is an effective way to achieve large travel range and high resolution, the coordinated controller with multiple actuation modes should be studied and designed, and suitable actuation mode is selected under suitable condition and moment, the actuation aim can be achieved by the coordination of the actuation modes.

(4) Improvement of actuation modes and exploring new actuation modes to achieve the high accuracy and large travel range. The idea that one actuator can operate at different actuation modes is proposed, the high accuracy can be achieved by the direct actuation mode, and the large travel range can be achieved by the stepping motion of the output platform when operating at the resonance, inertial or clamping and feeding actuation modes, the related research should be performed in the future.

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