This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3285271

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2023.Doi Number

An Inchworm and Stick-slip Dual Mode Piezoelectric Linear Actuator for Cell Injection

Jijie Ma[1,2], Junhao Li[3], Xiaohui Lin[2], Xinsheng He[1], Yili Hu[1,2], Jianping Li[1,2], Jianming Wen[1,2]

[1]Key Laboratory of Urban Rail Transit Intelligent Operation and Maintenance Technology & Equipment of Zhejiang Province, Zhejiang Normal University, *Jinhua* 321004,China
[2]Institute of Precision Machinery and Smart Structure, College of Engineering, Zhejiang Normal University, Jinhua 321004, China
[3]College of Physics and Electronic Information Engineering, Zhejiang Normal University, Jinhua 321004, China

Corresponding author: Xinsheng He (xsh@zjnu.cn); Jianming Wen (wjming@zjnu.cn)

This work was supported in part by the Zhejiang Provincial Natural Science Foundation of China under Grant LQ21E050013, in part by the Zhejiang Provincial Key Research and Development Project of China under Grant 2021C01181.

ABSTRACT Cell injection system for biomedical engineering demands that actuators have large stroke, high resolution and speed for cell positioning and injection. Single mode piezoelectric actuators could meet some of these requirements but hardly all. Stick-slip actuator is easy to achieve high-speed operation, but it is prone to setback; The speed characteristics of the inchworm actuator are lower than those of the stick-slip actuator, but the step is more stable and the setback is lower. This study proposes an inchworm and stick-slip dual mode piezoelectric actuator (ISSPA) for cell injection. It integrates two working modes into one actuator and both modes drive the same slider. The stick-slip mode works at high frequency for fast positioning to the cell and the inchworm mode drives the needle to puncture the cell membrane and accurately locates to the specified location. The structure and working principle of the ISSPA are provided. A prototype of the proposed ISSPA is fabricated and experiments are conducted. When the driving voltage of the piezoelectric stack is 100 V and the frequency is 500 Hz,the maximum speed of the ISSPA is 2.287 mm/s in the stick-slip mode. When the driving voltage of the piezoelectric stack is 60 V, the frequency is 3 Hz and the load is 0.5 kg,the minimum step displacement is 57 nm in inchworm mode. Demonstration of cell injection is carried out by using the ISSPA to positioning and puncturing a zebrafish embryo. Fast positioning with the stick-slip mode and accurate puncture with the inchworm mode are achieved with the ISSPA alone, taking 12 seconds for the whole injection process. It could be expected to apply the ISSPA to cells with wide range of diameter, as the frequency of the stick-slick mode and the voltage of the inchworm mode could be well regulated.

INDEX TERMS Piezoelectric actuator, cell injection, dual mode

I. INTRODUCTION

Cell manipulation is a research hotspot in recent years along with the fast development of biomedical engineering [1]-[3]. One of the typical operation of cell manipulation is single cell injection. Since many cell drugs like cyclic peptides are impermeable to the cell membrane, preventing their application against intracellular targets [4], cell injection provides a solution of cell membrane puncture and drug delivery. Cell injection usually works after the preparations including cell selection, capture, posture adjustment and hold which are guided by an electronic optical amplification system [5], [6]. When the cell is fixed by the holder, a glass injection needle driven by a linear actuator approaches the cell and punctures the cell membrane. Then the drug could be delivered. As the scale of cells is widely distributed from several microns in red blood cells [7] to nearly millimeter in oocytes [8], the resolution of the linear actuator should be at the micron or even submicron level. The travel in the approaching stage also varies greatly depending on the view magnification of the CCD in the electronic optical system. Thus linear actuators with large stroke, high resolution and speed is crucial and urgent in need for cell injection system.

Piezoelectric actuator (PA), driven by the micro-deformation of piezoelectric ceramics (PZT), is a promising competitor in precision positioning system [9]. Compared with electromagnetic motors (EM), PAs have the advantages of simple structure, no electromagnetic interference and fast response. According to the vibration state, PAs can be divided into resonant and non-resonant actuators [10]. Resonant actuators, also known as ultrasonic motors, have linear speed from dozens to hundreds of mm/s [11], [12]. Non-resonant actuators, including inchworm, direct drive and inertial PAs, have high resolutions from microns to nanometers [13], [14]. However, the requirement of large stroke, high resolution and speed in cell injection system is still a challenge for PAs due to the shortcomings inherited from the working principle. Ultrosonic motors demand high resolution displacement sensors as feedback for precise positioning. Direct drive PA has limited stroke. Low speed of inchworm PA and backward motion of inertial PA limit their application in cell injection system. Researchers proposed many improvements to PAs, attempting to reduce or eliminate the influence of these shortcomings. Sun etc. [15] adopted flexible supporting baffles to increase the speed of inchworm PA upto 5.1 mm/s, but the resolution of the PA was dramatically reduced as well. A previous study of ours adjusted the electrical connections of inertial PA and successfully eliminate the backward motion [5], but the step displacement and speed behaviour were not perfect. Meantime, cells exhibit plastic deformation when large deformation is undergone [16]. Thus stair like steps with steep rising edge, typical outputs of inchworm PA, are better than the sawtooth displacement from the perspective of protecting cells.

A possible solution to fully play the advantages of each actuator is the integration of two or more actuators. Integration of EM and PA, named macro-micro composite drive, has been studied by some researchers and granted the EMs positioning precision from sub-micron to nanometer level [17], [18]. But EM-PA composite drive involves two independent devices, which makes it large in size and brings residual vibration during mode switch. In this study, an inchworm and stick-slip dual mode PA is proposed for cell injection. Combining the inchworm and stick-slip mode in one PA, the proposed actuator is integrated in structure. The fast speed stick-slip mode is used for positioning and the inchworm mode is used for injection to avoid the risk of cell damage due to backward motion. The structure and working principle of the ISSPA is discussed in section 2. Parameter optimization and performance experiments are presented in section 3. Demonstration of cell injection using the two modes is presented after that. It will be shown that the ISSPA is a promising solution of cell injection.

II. STRUCTURE AND WORKING PRINCIPLE

The structure of the proposed ISSPA follows inchworm actuators, with slight modifications to adapt the stick-slip mode. A typical inchworm actuator includes two clamping units and a driving unit. Two electromagnets are selected to clamp the slider. The driving circuit of the electromagnet is simpler, such as the H-Bridge circuit, which can complete the control of the electromagnet. The price of a single electromagnet is about $4.33, while the price of a single piezoelectric stack is about $216.75, so the clamping method using electromagnets is cheaper than the traditional method using piezoelectric stacks. The structure of the proposed actuator is demonstrated in Figure 1(a), and the structure of the flexure hinge is demonstrated in Figure 1(c). Electromagnets are fixed on the moving part of the flexure hinges which are integrated on the base. The slider, made of 1j06 iron aluminum soft magnetic Alloy, is placed on the top of the electromagnets. In order to avoid the resistance from the other electromagnet in the stick-slip mode, two piezoelectric stacks are configured to move both clamping units at the same time.

The working principle of the actuator is shown in Figure 1(b) and Figure 1(d, e). The actuator has four working state: holding, stick-slip, braking and inchworm. The excitation sequences for these modes are illustrated in Figure 1(b). In the holding mode, both electromagnets are activated and both PZTs are deactivated. The slider holds the current position with holding force from the EMs. In the stick-slip mode, both electromagnets get deactivated after degaussing and both PZTs are driven by sawtooth wave signal featured slow rising and fast falling, as shown in Figure 1(b) step ① and step ②. The slider moves a big step (S_1) forward and a small step (S_2) backward,following the typical rule of stick-slip actuators [14] as shown in Figure 1(d). Braking mode works as a transition mode for the fast switchover to the inchworm mode. In this mode, both PZTs get deactivated and the two electromagnets get activated to provide a large braking force. The inchworm mode is designed for the precise adjustment in cell penetration, generating small and stable steps at low speeds. The excitation sequence and realtime status of the inchworm mode are shown in Figure 1(b) and (e), respectively. As shown in Figure 1(b) step ③, EM2 gets deactivated after degaussing, while EM1 is activated and holds the slider. Then in Figure 1(b) step ④, PZT1 is elongated by a signal with slope duration TR to move the slider a step S forward. In Figure 1(b) step ⑤ and step ⑥, after both electromagnets inversing their status, PZT1 contracts back to the initial position while the slider holds the current position. With the above working modes, the actuator suits cell penetration well: the stick-slip mode for fast approaching, the inchworm mode for stable penetration, the braking mode for transition.

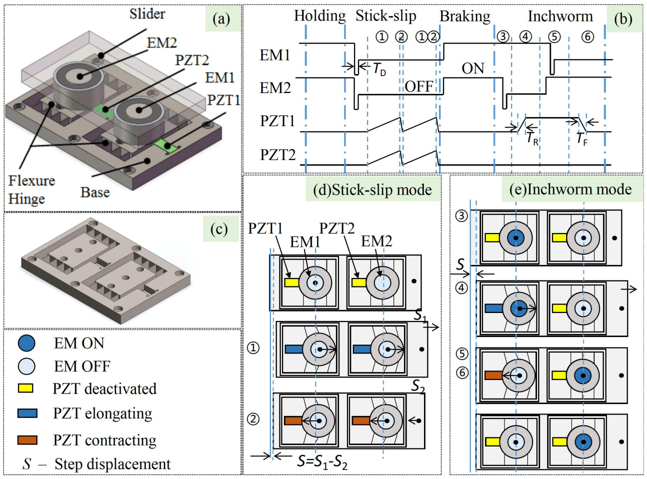

FIGURE 1. **The structure and working principle of the actuator: (a)The structure of the ISSPA; (b) The sequence of the excitation signals; (c) The structure of the flexure hinge; (d)The movement of stick-slip mode; (e)The movement of inchworm mode.**

III. EXPERIMENTS

A. EXPERIMENTAL SETUP

A prototype and driver of the proposed actuator were fabricated according to the working principle, as illustrated in Figure 2(a). The piezoelectric stacks (MTP150/5×5/18, Coremorrow, China) are 5 mm×5 mm×18 mm in size, the detailed parameters are shown in Table 1. Electromagnets are commercial ones with the surface processed by abrasive machining for better contact. The driver of actuator includes a controller, a touch screen, two piezoelectric amplifiers, two H-bridges for electromagnets, and a supply system. User commands are given from the touch screen. The controller generates the sequenced driving signals and switches the actuator to the appropriate mode according to the commands.

TABLE I
Parameters of piezoelectric stack

Parameter	Value
Driving voltage	0-150 V
Travel (0-150 V)	20 μm±15%
Hysteresis	15%
Recommended load	400 N
Stiffness	50 N/μm±20%
No load resonant frequency	70 kHz
Capacitance	1.6 μF±15%

A testing system was also established to measure the performance of the actuator, as shown in Figure 2(b). A laser displacement sensor (LK-HD500, Keyence Corporation, Japan) is fixed beside the actuator to detect the displacement of the slider. The displacement data of the sensor are collected with a computer. A high speed camera (VH-S30, Keyence Corporation, Japan) is used to record the penetrating process. All the instruments and the actuator are placed on a vibration isolation table to reduce the interference from environment. The driving part includes a driver chip (L298N) for controlling the electromagnets, a customized power amplification module (amplification factor of 20, output voltage range of 0-100 V) for driving the piezoelectric stack, and a control module (stm32f407).

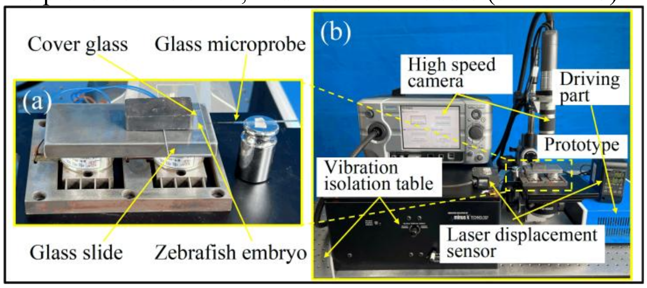

FIGURE 2. **The prototype and testing system: (a)The prototype; (b)The testing system**

B. PARAMETERS OPTIMIZATION

1) DEGAUSSING TIME OF THE ELECTROMAGNET

As the clamping component, electromagnet brings residual magnetism along with the convenience in design. Thus degaussing has to be considered before application. Negative pulse is selected for degaussing in this study. A negative pulse with duration T_D (the degausing time) is added to the end of each excitation cycle of the electromagnet. The degaussing time T_D is optimized by evaluating the residual magnetic force F_D which is the difference between the measured dragging force F_{D0} and the slider weight m_{SG}. The residual magnetic force versus negative pulse duration is shown in Figure 3. The minimum F_D emerges when T_D is 65 ms. Larger T_D will enlarge F_D due to reverse magnetization. Thus we select 65 ms as the degaussing time.

2) RISING/FALLING TIME OF THE PIEZOELECTRIC VIBRATOR

Fast response of the piezoelectric stack may lead to slip between the clamping component and the output slider due to the high acceleration. Trapezoidal wave is a solution to relieve the slip [19]. The rising and falling time (T_R and T_F, $T_R = T_F$) of the trapezoidal wave are studied in this section. Step displacement is an indicator of slip where larger slip leads to smaller displacement. The step displacements are observed as the rising/falling time increases from 1 ms to 35 ms. As shown in Figure 4, the step displacement goes up dramatically before 10 ms and keeps almost stable hereafter. Considering shorter rising/falling time benefits the working frequency range of the piezoelectric stack, 10 ms is selected as the rising/falling time of the trapezoidal wave.

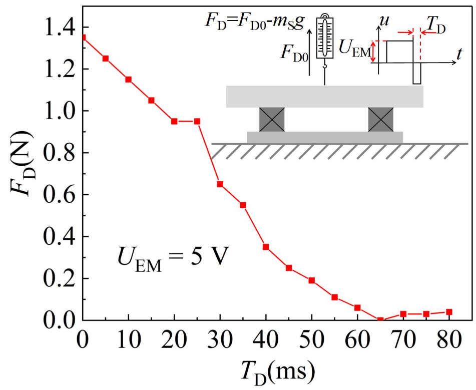

FIGURE 3. **The residual magnetic force at different degaussing time**

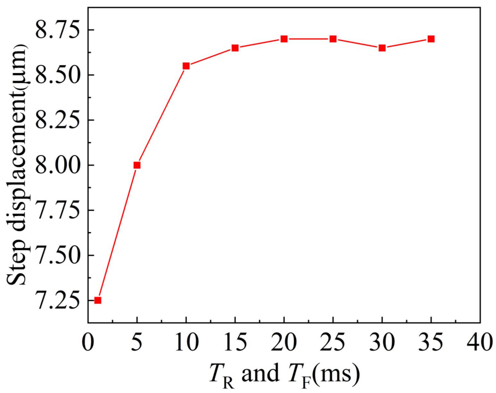

FIGURE 4. **The step displacement at different rising/falling time of the piezoelectric stack.**

C. PERFORMANCE TEST OF THE INCHWORM MODE

1) VOLTAGE AND FREQUENCY CHARACTERISTIC

Frequency characteristic is conducted in the range of 1 Hz to 5 Hz due to the limitation of the time constants, such as the degaussing time, the rising and falling time of the piezoelectric vibrator, etc. The step displacement has small fluctuation as the frequency increases, as shown in Figure 5. Similar trend of frequency characteristic happens to all five voltages. Thus excitation voltage is the recommended parameter to control the step displacement of the actuator in inchworm mode. When the excitation voltage of the piezoelectric vibrator is 100 V, the relationship between the regression rate and frequency of 10 steps randomly selected is shown in Figure 6. At 3 Hz, the fallback rate is the lowest, and at this time, the fallback rate is 10.5%. So the recommended frequency is 3 Hz. The reason for the setback of the inchworm mode is the vibration generated by the degaussing signal when degaussing the electromagnet.

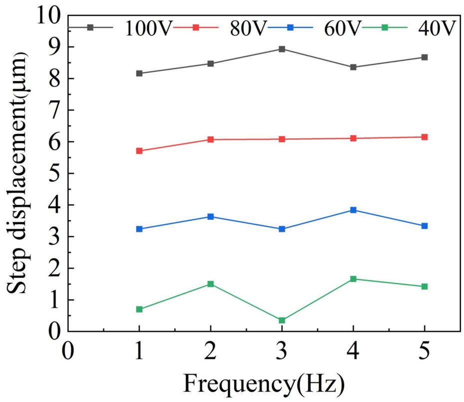

FIGURE 5. **Frequency characteristic of the inchworm mode.**

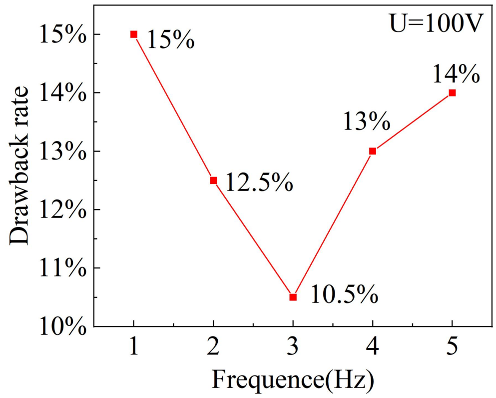

FIGURE 6. **Drawback characteristic of the inchworm mode.**

A significant parameter of the piezoelectric actuator output performance is the step displacement which greatly affect the resolution of actuators. The step displacement at different voltages are studied without load, as illustrated in Figure 8. The start voltage of the actuator is 40 V. The step displacement demonstrates linear growth as the excitation voltage of the piezoelectric vibrator goes from 40 V to 100 V. The minimum no-load step displacement is 0.36 μm at 40 V and the maximum one is 8.94 μm at 100 V. Figure 7 further demonstrates the step characteristic which has good linearity at working voltages.

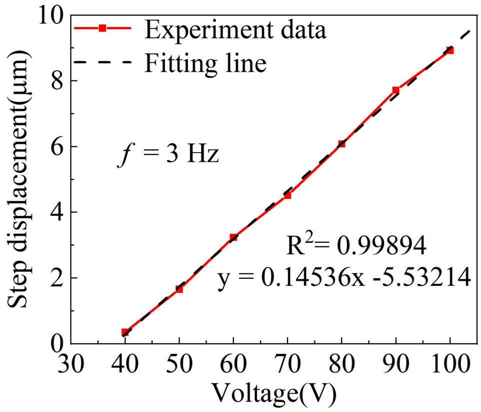

FIGURE 7. Voltage characteristic of the inchworm mode.

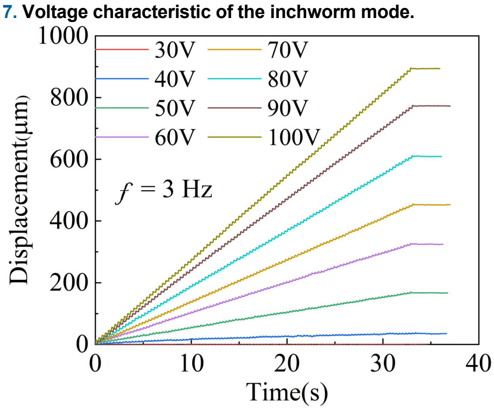

FIGURE 8. Step characteristic of the inchworm mode.

2) LOAD CHARACTERISTIC

Load characteristic of the inchworm mode is carried out by adding weights to the slider. Both the speed and step displacement are tested at different loads. As illustrated in Figure 9(a), the speed of the slider decreases as more weights are added. The figure shows the fitting curve and goodness of fit(R^2) before the weight is 3.5 kg. The speed demonstrates approximate linear relationship with weight as the weight goes from null to 3.5 kg. Although the actuator in inchworm mode could carry more than 3.5 kg but it suffers from a significant speed decrease above 3.5 kg. Thus the recommended load capacity is 3.5 kg. Frequency is the decisive parameter of the speed of the inchworm mode, higher frequency generating higher speed in the whole range of load. The step displacement decreases with load and excitation voltage, as shown in Figure 9(b). High voltage, maximum 100 V in this study, is the choice for heavy loads. The minimum step displacement is 57 nm when the excitation voltage is 60 V and the weight is 1 kg. The load characteristic shows that inchworm mode excels at step displacement instead of speed.

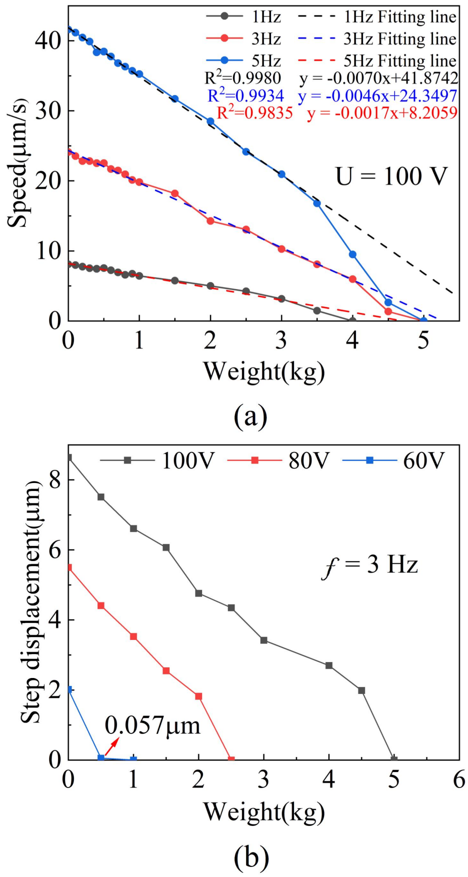

FIGURE 9. Load characteristic of inchworm mode: (a) speed versus weight; (b) Step versus weight.

D. PERFORMANCE TEST OF THE STICK-SLIP MODE

1) FREQUENCY CHARACTERISTIC

Stick-slip piezoelectric actuators have relatively large speed in non-resonant actuators, usually in the level of mm/s [14], [20]. Consider the speed requirement of the stick-slip mode in this design, the maximum excitation voltage (100 V) is selected to find the largest possible speed. Figure 10(a) shows the step characteristic of the stick-slip mode. The actuator moves step by step in a linear way, a typical stick-slip step characteristic. Figure 10(b) shows the speed performance at different frequencies. The maximum speed is 2.287 mm/s when the frequency is 500 Hz. Higher frequencies above 500 Hz failed to generate higher speed due to the larger backward motion. Recommended range of frequency is 0 to 350 Hz where the speed is approximately proportional to frequency.

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3285271

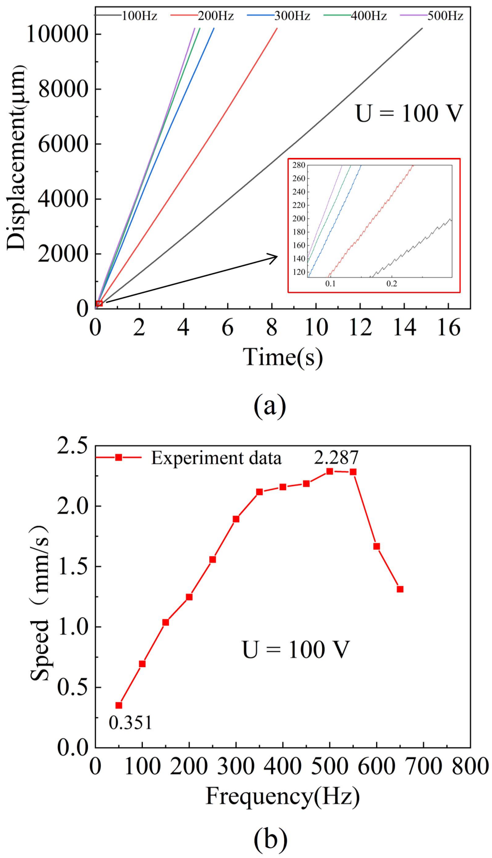

FIGURE 10. **Frequency characteristic of the stick-slip mode: (a) Step behaviour; (b) Speed behaviour.**

2) LOAD CHARACTERISTIC

Load capability of the stick-slip mode is tested in this section, as illustrated in Figure 11. The speed of the actuator in stick-slip mode decreases a little as the carrying weight goes from 0 to 3.5 kg. Dramatic decreases of speed happen at weights above 3.5 kg. Thus the appropriate load of the stick-slip mode is no more than 3.5 kg where the actuator could move at speed higher than 1.6 mm/s.

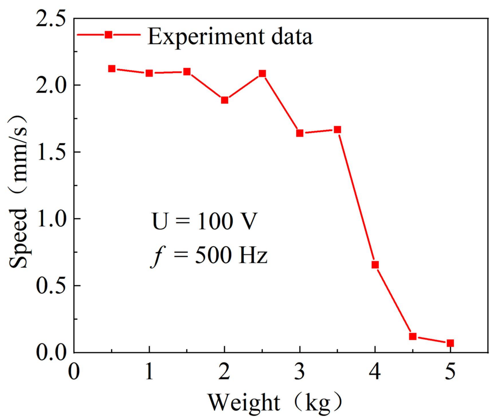

FIGURE 11. **Load characteristic of the stick-slip mode.**

E. DEMONSTRATION

Penetration of cells driving by the proposed actuator is demonstrated in this section. A zebrafish embryo with the diameter of around 1,700 μm is placed on the slider of the actuator, and a glass microprobe is fixed in front of the embryo. The injection process includes two stages: fast positioning to the embryo with the stick-slip mode, injecting the embryo with the inchworm mode. The whole process is recorded with a high speed camera and the displacement of the slider is measured with a laser displacement sensor. The result is shown in Figure 12 and the video is attached in the supplement. The actuator starts moving from t_1 in stick-slip mode with the driving voltage and frequency of 100 V and 100 Hz, respectively. The positioning motion stops at t_2 where the tip of the glass microprobe is close to the cell membrane. In this stage, the speed of the actuator is 6.3 mm/s. Penetration begins right after the positioning stage and the actuator is switched to inchworm mode. The microprobe penetrates step by step until reaching the injecting position at t_3.The stick-slip mode makes cell to approach the glass microprobe in a short time, and the inchworm mode successfully pierces the cell membrane and locates to the predetermined position.

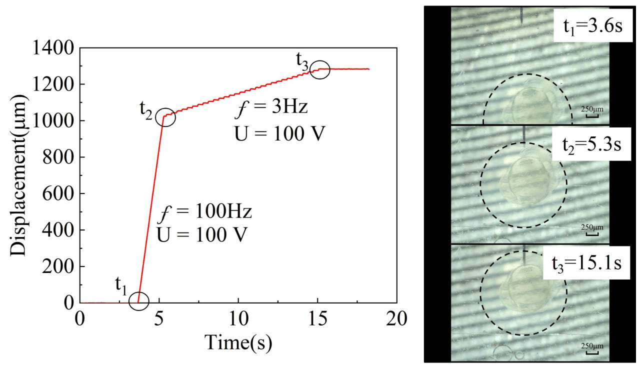

FIGURE 12. **Cell injection with the stick-slip and inchworm mode.**

IV. DISCUSSION

Table 2 compared the performance of the proposed actuator with those piezoelectric actuators in the literature. It can be seen that the proposed actuator can not only have fast driving speed, but also maintain high driving accuracy.

TABLE II
Comparison of the proposed actuator with those in the literature

Authors	Driving principle	Maximal velocity	Minimum step
Hu *et al.* [5]	Stick-slip	7.880 μm/s	0.320 μm
Deng *et al.* [21]	Stick-slip	382 μm/s	2.47 μm
Lu *et al.* [22]	Inchworm	1250.4 μm/s	0.5837 μm
Wang *et al.* [23]	Inchworm	41.3 μm/s	0.241 μm
Dong *et al.* [24]	Inchworm	0.72 mm/s	/
Shao *et al.* [25]	Hybrid	0.043 mm/s	80 nm
This paper	Inchworm and Stick-slip	2.287 mm/s	57 nm

The proposed actuator could work in inchworm and stick-slip mode independently. Thus it demonstrates the superiorities of both modes and makes up the deficienies by the other mode. As illustrated in the injection experiment, the actuator locates the embryo with stick-slip mode and injects the embryo with inchworm mode. The coordination of the two modes realizes fast moving and stable injection. Electromagnets clamped inchworm actuators suffer from the low speed due to frequency limitation. The stick-slip mode upgrades the speed of inchworm actuators to the level of mm/s.

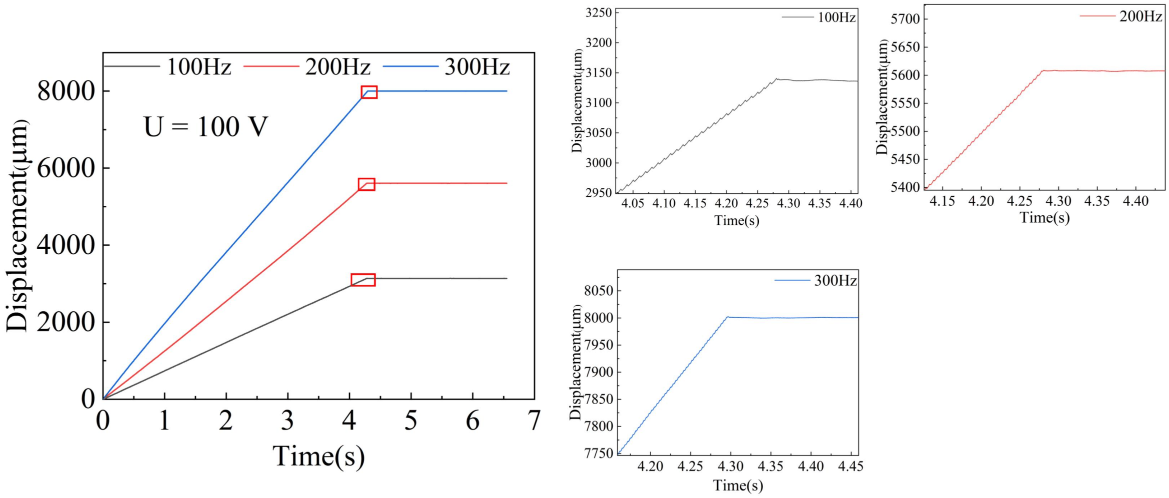

FIGURE 13. Mode switching stability at different frequencies.

Mode switch is a troublesome problem for hybrid actuators. ZHANG etc.[18] discussed the settling time during the macro-micro switch due to the residual vibration from the macro motion. A rapid dynamic positioning method was proposed to quickly reduce the settling time by employing a designed spring-piezoelectric microstage. For rapid vibration reduction, CHEN etc. proposed an event-triggered adaptive control scheme based on backstepping technique and radial basis function neural networks [26]. These studies adopt complex control scheme and special purpose vibration reduction structure to reduce the residual vibration. The ending of the macro motion in this study, e.g. the stick-slip mode, was also observed. The result is shown in Figure 13 and the residual vibration of the macro motion did not happen. On the one hand, the stick-slick mode moves in stepping motion instead of continuous one. It is easier to brake the slider at the stick stage, especially with the coordination of the two clamping electromagnets. On the other hand, the two modes of the actuator in this study share the same slider. This is quite different from the macro-micro composite stages above whose micro stage and slider move together by the macro stage.

V. CONCLUSION

An inchworm and stick-slip dual mode piezoelectric actuator is proposed for cell injection where the stick-slip mode is designed for fast positioning and the inchworm mode is for puncture. The structure design and working principle of the ISSPA are provided. Experiments and demonstration of cell injection are carried out. The following conclusions can be made from the study:

1) The proposed ISSPA can work in inchworm and stick-slip mode, which brings the maximum speed of 2.287 mm/s in the stick-slip mode and the minimum step displacement of 57 nm in the inchworm mode.

2) Cell injection with the proposed ISSPA can be carried out by fast positioning to the cell with the stick-slip mode and puncture the cell membrane with inchworm mode.

3) The switchover between the stick-slip and inchworm mode does not bring vibration thanks to the electromagnet clamps and the share of same output slider of the two modes.

With the same principle but different parameters, the proposed actuator could be further applied in other fields, such as 3D printers, machine feeding, etc.

REFERENCES

[1] D. Ahmed, A. Ozcelik, N. Bojanala, N. Nama, A. Upadhyay, Y. C. Chen, W. Hanna-Rose, and T. J. Huang, "Rotational manipulation of single cells and organisms using acoustic waves," Nature Communications, vol. 7, Mar, 2016.

[2] X. Y. Ding, S. C. S. Lin, B. Kiraly, H. J. Yue, S. X. Li, I. K. Chiang, J. J. Shi, S. J. Benkovic, and T. J. Huang, "On-chip manipulation of single microparticles, cells, and organisms using surface acoustic waves," Proceedings of the National Academy of Sciences of the United States of America, vol. 109, no. 28, pp. 11105-11109, Jul, 2012.

[3] M. Doumane, M. C. Caillaud, and Y. Jaillais, "Experimental manipulation of phosphoinositide lipids: from cells to organisms," Trends in Cell Biology, vol. 32, no. 5, pp. 445-461, May, 2022.

[4] P. G. Dougherty, A. Sahni, and D. H. Pei, "Understanding Cell Penetration of Cyclic Peptides," Chemical Reviews, vol. 119, no. 17, pp. 10241-10287, Sep, 2019.

[5] Y. Hu, J. J. Ma, Y. Zhang, J. P. Li, Y. L. Hu, and J. M. Wen, "Performance comparison of two motion modes of a piezoelectric inertial linear motor and its potential application in cell manipulation," Mechanical Systems and Signal Processing, vol. 157, Aug, 2021.

[6] M. Y. Hsu, Y. T. Huang, C. J. Weng, C. M. Chen, Y. F. Su, S. Y. Chu, J. H. Tseng, R. C. Wu, and S. J. Liu, "Preparation and in vitro/in vivo evaluation of doxorubicin-loaded poly lactic-co-glycol acid microspheres using electrospray method for sustained drug delivery and potential intratumoral injection," Colloids and Surfaces B-Biointerfaces, vol. 190, Jun, 2020.

[7] T. Matsuhira, and H. Sakai, "Artificial oxygen carriers, from nanometer- to micrometer-sized particles, made of hemoglobin composites substituting for red blood cells," Particuology, vol. 64, pp. 43-55, May, 2022.

[8] M. Kobayashi, A. Jamieson-Lucy, and M. C. Mullins, "Microinjection Method for Analyzing Zebrafish Early Stage Oocytes," Frontiers in Cell and Developmental Biology, vol. 9, Nov, 2021.

[9] Y. X. Liu, J. Li, J. Deng, S. J. Zhang, W. S. Chen, H. Xie, and J. Zhao, "Arthropod-Metamerism-Inspired Resonant Piezoelectric Millirobot," Advanced Intelligent Systems, vol. 3, no. 8, Aug, 2021.

[10] L. Wang, W. S. Chen, J. K. Liu, J. Deng, and Y. X. Liu, "A review of recent studies on non-resonant piezoelectric actuators," Mechanical Systems and Signal Processing, vol. 133, Nov, 2019.

[11] L. Wang, T. Wielert, J. Twiefel, J. Jin, and J. Wallaschek, "A rod type linear ultrasonic motor utilizing longitudinal traveling waves: proof of concept," Smart Materials and Structures, vol. 26, no. 8, Aug, 2017.

[12] Y. Jian, Z. Y. Yao, and V. V. Silberschmidt, "Linear ultrasonic motor for absolute gravimeter," Ultrasonics, vol. 77, pp. 88-94, May, 2017.

[13] Y. Y. Gao, J. M. Wen, J. J. Ma, Y. Zhang, R. M. Wang, Y. L. Hu, and J. P. Li, "A self-adapting linear inchworm piezoelectric actuator based on a permanent magnets clamping structure," Mechanical Systems and Signal Processing, vol. 132, pp. 429-440, Oct, 2019.

[14] J. P. Li, H. Huang, and T. Morita, "Stepping piezoelectric actuators with large working stroke for nano-positioning systems: A review," Sensors and Actuators a-Physical, vol. 292, pp. 39-51, Jun, 2019.

[15] T. T. Sun, and P. Yan, "A novel high-speed bi-directional piezoelectric inchworm actuator based on flexible supported baffles," Smart Materials and Structures, vol. 31, no. 9, Sep, 2022.

[16] P. Y. Wang, and Q. S. Xu, "Design and Testing of a Flexure-Based Constant-Force Stage for Biological Cell Micromanipulation," IEEE Transactions on Automation Science and Engineering, vol. 15, no. 3, pp. 1114-1126, Jul, 2018.

[17] A. T. Salton, M. Y. Fu, J. V. Flores, and J. C. Zheng, "High Precision Over Long Range: A Macro-Micro Approach to Quantized Positioning Systems," IEEE Transactions on Control Systems Technology, vol. 29, no. 6, pp. 2406-2415, Nov, 2021.

[18] L. Y. Zhang, J. Gao, and X. Chen, "A Rapid Dynamic Positioning Method for Settling Time Reduction Through a Macro-Micro Composite Stage With High Positioning Accuracy," IEEE Transactions on Industrial Electronics, vol. 65, no. 6, pp. 4849-4860, Jun, 2018.

[19] J. Deng, Y. X. Liu, J. K. Liu, D. M. Xu, and Y. Wang, "Development of a Planar Piezoelectric Actuator Using Bending-Bending Hybrid Transducers," IEEE Transactions on Industrial Electronics, vol. 66, no. 8, pp. 6141-6149, Aug, 2019.

[20] Z. Xu, H. Huang, and J. S. Dong, "A stick-slip piezoelectric actuator with measurable contact force," Mechanical Systems and Signal Processing, vol. 144, Oct, 2020.

[21] J. Deng, S. H. Liu, Y. X. Liu, L. Wang, X. Gao, and K. Li, "A 2-DOF Needle Insertion Device Using Inertial Piezoelectric Actuator," IEEE Transactions on Industrial Electronics, vol. 69, no. 4, pp. 3918-3927, Apr, 2022.

[22] Q. T. Lu, J. J. Ma, X. H. Lin, Y. L. Hu, J. P. Li, and J. M. Wen, "The Development of Piezoelectric Inchworm Actuator Clamped With Magnetorheological Elastomer and Its Potential Application in Brain -Computer Interface Implantation," IEEE Transactions on Industrial Electronics, vol. 70, no. 4, pp. 4018-4026, Apr, 2023.

[23] R. M. Wang, Y. L. Hu, D. Z. Shen, J. J. Ma, J. P. Li, and J. M. Wen, "A Novel Piezoelectric Inchworm Actuator Driven by One Channel Direct Current Signal," IEEE Transactions on Industrial Electronics, vol. 68, no. 3, pp. 2015-2023, Mar, 2021.

[24] H. J. Dong, T. J. Li, Z. W. Wang, and Y. M. Ning, "Design and experiment of a piezoelectric actuator based on inchworm working principle," Sensors and Actuators a-Physical, vol. 306, May, 2020.

[25] S. B. Shao, S. Y. Song, Y. Shao, and M. L. Xu, "Long-range piezoelectric actuator with large load capacity using inchworm and stick-slip driving principles," Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology, vol. 75, pp. 167-179, May, 2022.

[26] X. Chen, Y. Liu, L. Y. Zhang, J. Gao, B. Yang, and X. Chen, "Event-Triggered Adaptive Control Design With Prescribed Performance for Macro-Micro Composite Positioning Stage," IEEE Transactions on Industrial Electronics, vol. 68, no. 10, pp. 9963-9971, Oct, 2021.

JIJIE MA was born in Tianjin, China, 1980. He received the Ph.D. degree in mechanical engineering from Jilin University, Changchun, China, in 2010. He is currently working as an Associate Professor in Zhejiang Normal University, Jinhua, China. His current research interests include triboelectric nanogenerators, piezoelectric actuators and motors.

JUNHAO LI was born in Qingdao, China, in 1999. He received the B.S. degree in Electronic Information Technology from Civil Aviation Flight University of China, Guanghan, China, in 2017. He is currently pursuing the M.S. degree in Electronic Information Technology, Zhejiang Normal University, Jinhua, China. His main research interest includes piezoelectric drive.

XIAOHUI LIN was born in Jinhua, China, in 2000. He is currently pursuing the bachelor ' s degree with Zhejiang Normal University, Jinhua, China. His main research interest includes piezoelectric drive.

XINSHENG HE was born in Henan, China, in 1979. He is currently working as an Associate Professor in Zhejiang Normal University, Jinhua, China. His current research interests include triboelectric nanogenerators, Intelligent precision manufacturing, Photovoltaic power generation technology and application.

YILI HU was was born in Hangzhou, China, in 1989. He received the B.S. degree in mechanical design, manufacturing, and automation, and the M.S. degree in physical electronics from Zhejiang Normal University, Jinhua, China, in 2008 and 2012, respectively, and the Ph.D. degree from Shanghai Jiao Tong University, Shanghai, China, in 2020. He is currently working as a Associate Professor with Zhejiang Normal University. His current research interests include piezoelectric actuators, sensors, triboelectric nanogenerators and energy harvesters.

JIANPING LI was born in Jiangsu, China, in 1987. He received the B.S. degree and Ph. D degree from the School of Mechanical Science and Engineering, Jilin University, Changchun, China, in 2011 and 2016, respectively. After that, he worked in Chiba University as a JSPS researcher in Japan, supported by the Japan Society for the Promotion of Science (JSPS).
From 2018, he come back to China, and works in the institute of precision machinery and smart structure, College of Engineering, Zhejiang Normal University. His current research interests include piezoelectric actuator based nano-positioning systems, and the application of electrical impedance spectroscopy in biomedical science.

JIANMING WEN was born in Hebei, China, in 1980. He received the B.S. degree in mechanical engineering and automation, and the M.S. and Ph.D. degrees in mechanical and electronic engineering from Jilin University, Changchun, China, in 2003, 2006, and 2009, respectively. He is currently a Professor with Zhejiang Normal University, Jinhua, China. His current research interests include piezoelectric drive and control technology.