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Simple new ultrasonic piezoelectric actuator for precision linear positioning

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Abstract This paper presents a new linear piezoelectric actuator for linear translation. The positioning stage driven by the actuator has a very simple and compact structure consisting of a linear guide and the linear piezoelectric actuator. The operation principle of the linear piezoelectric actuator is first described. Then, the characteristics of the positioning stage are investigated. Experiments indicate that the step size is adjustable and the minimum is 26 nm with an inertial mass of 100 g in the open-loop condition; the stage motion driven by the actuator is controlled to the target position plus or minus <1 μm within 330 ms for a traveling distance of 10 mm in the closed-loop condition.

Keywords Precision positioning · Ultrasonic · Linear motor · Piezoelectric

1 Introduction

With the rapid development of high-tech fields, such as semiconductor equipment, fiber optics manufacturing and dynamic components, bio-medical and pharmaceutical manufacturing, there are great demands in precise manufacturing, measurement, and machining processes. Currently, linear actuators are an excellent solution for precise positioning applications that require rapid response and high positioning accuracy because of their feature of direct driving. Nowadays, many types of linear precision actuators, such as magnetic linear actuators [1–3] and piezoelectric actuators [4–6], have been developed. Compared with magnetic linear actuators, piezoelectric actuators have many attractive advantages such as mechanical simplicity, quick response, and electromagnetic immunity. Generally, piezoelectric actuators can be classified into two categories, based on the type of driving voltage applied to the device and the nature of the strain induced by the voltage [7]: (1) rigid displacement devices for which the strain is unidirectionally induced along an applied DC field, and (2) resonating displacement devices for which the alternating strain is excited by an AC field at the mechanical resonance frequency. The former can produce small displacements with high resolution (sub-nanometer) over small travel ranges (several micrometers) [8] and has been thus used in many fields [8–10]. However, their travel ranges are limited by the dielectric strength and thickness of the piezoelectric material. The latter is linear ultrasonic motors [7, 11–13] ,which can provide longer travel ranges (no limited in theory) via the repetition of many small steps (several nanometers to micrometers in size) that are generated by piezoelectric actuators. Furthermore, precise open-loop operation, and holding position without energy consumption are also attractive features of linear ultrasonic motors. Consequently, all these features make the linear ultrasonic motor widely used as direct-drive module in many applications that require long travel and high positioning accuracy (http://www.physikinstrumente.com/en/

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In this paper, the fundamental configuration and operating principle of the actuator are first described briefly. Then, the driving method is introduced and the motion control

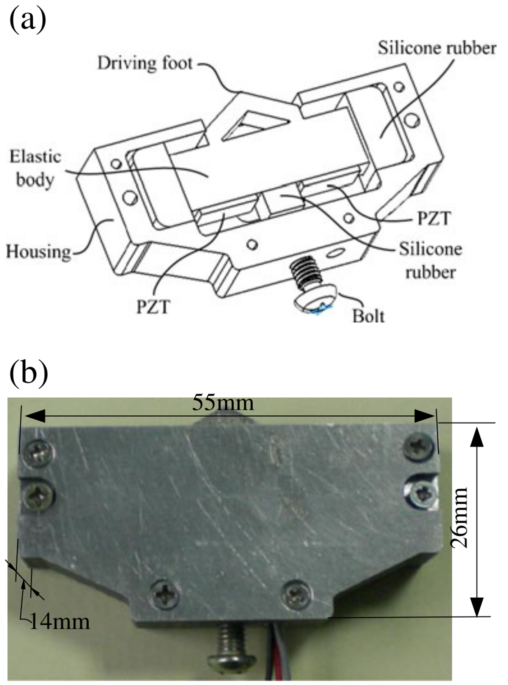


Fig. 1 Piezoelectric linear actuator: (**a**) structure and (**b**) prototype

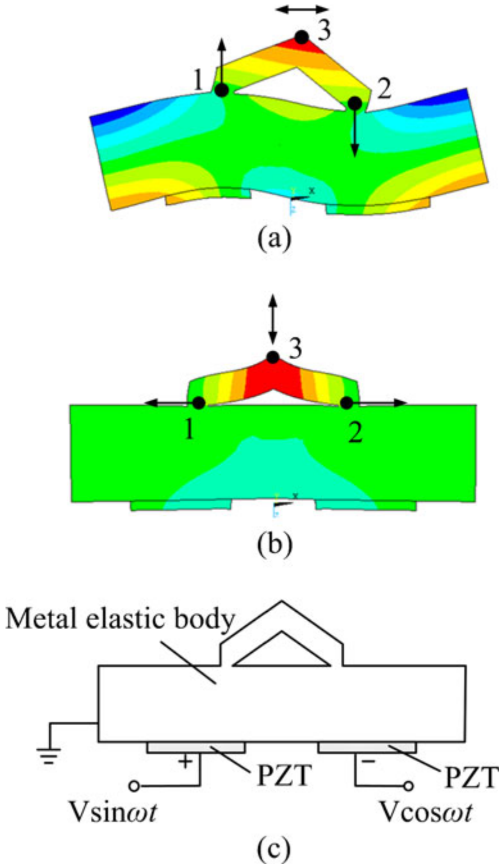
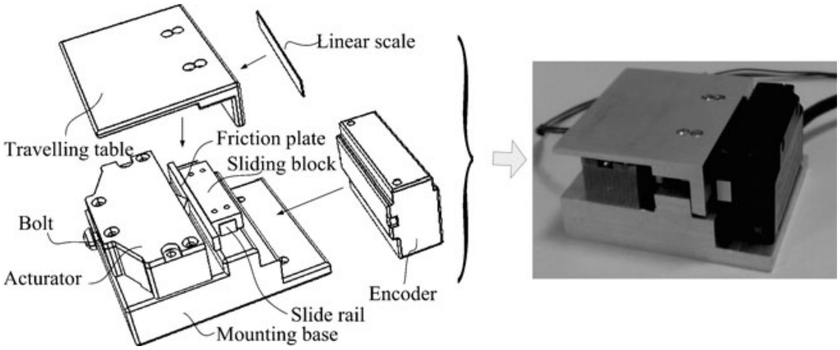


Fig. 2 Operation modes and excitation of the actuator: (**a**) B2 mode, (**b**) L1 mode and (**c**) excitation of the actuator

Fig. 3 Exploded view of positioning table and prototype



characteristics of the stage are investigated. The experiment results show that the actuator is capable of realizing good motion performance.

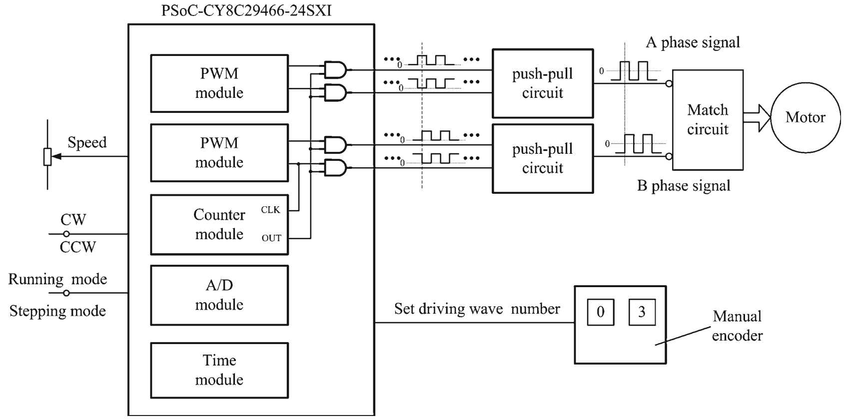
2 Actuator configuration and operating principle

The actuator used in the positioning system is of very simple design, as shown in Fig. 1. It consists of a metal thin plate and two rectangular piezoelectric ceramic plates polarized in the thickness direction. The piezoelectric ceramic plates are bonded on the bottom of the metal thin plate. The silicone rubbers, made from silicone elastomers and noted for its retention of flexibility, resilience, and tensile strength over a wide temperature range, are used as compliant suspension between the actuator's supporting structure and the actuator to decrease the influence caused by the clamping mode. A detailed view of the components in the actuator is shown in Fig. 1(a). Figure 1(b) is the prototype of the actuator. The whole dimension of the actuator is 55 mm × 26 mm × 14 mm.

The operating principle of the actuator is based on the resonant excitation of the first longitudinal vibration mode (L1) and the second bending vibration mode (B2) of the metal thin plate. Modal analysis results of the actuator are shown in Fig. 2. Two vertexes of the triangular structure of the actuator, point 1 and point 2, are designed on the crest of the B2 mode. In the state of the second bending mode, as shown in Fig. 2(a), point 1 moves downward and point 2 moves upward alternately and thus leading to a horizontal movement of point 3. In the state of the first longitudinal mode, as shown in Fig. 2(b), the movement of points 1 and 2 in the horizontal direction is amplified in the perpendicular direction through the triangular structure part. Therefore, a perpendicular movement of point 3 comes into being. Thus, if the two operating modes are actuated by voltage signals as shown in Fig. 2(c), there will be an elliptical trajectory on the tip of the driving foot and the slider pressed on it will be linearly driven. If the relative phase of the power source applied to the actuator is inverted, the motion direction of the slider will be reversed. As described above, the special design of the stator is that the displacement in the horizontal direction is amplified in the perpendicular direction through an isosceles triangular structure part of the metal thin plate when the actuator is operated in the first longitudinal mode.

Figure 3 shows the exploded view of the positioning stage. A commercially available slide bar can be used as the slider and a ceramic plate is bonded on the side of the sliding block to enhance the wear resistance. The travelling table is fixed on the sliding block. The pre-

Fig. 4 Hardware architecture block diagram of the driver based on PSoC



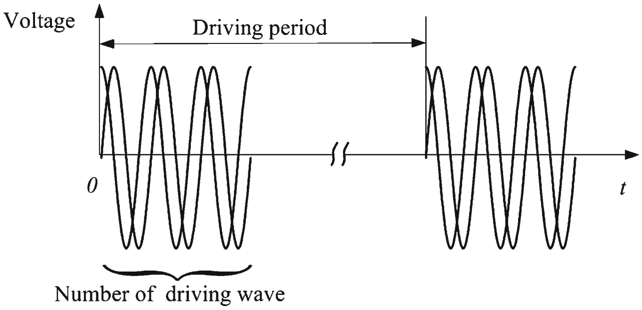


Fig. 5 Driving signal in stepping mode

load pushing the actuator against the ceramic plate is increased by tightening the adjustment screw, which increases the compression in the silicone rubber. A linear encoder is used to detect the position of the travelling table with a resolution of 1 μm.

3 Investigation of positioning stage characteristics

3.1 Driver of the actuator

Here, a commercially available Programmable System-on-Chip (PSoC) is used as the master controller, which can realize the function of frequency generating, frequency-divided and phase-divided, dead-zone regulating, and driving and control functions. The hardware architecture block-diagram of the driver is shown in Fig. 4. The four channel square waves with suitable phase difference, 5 V level, and 25–40 mA driving current can be directly generated by two PWM modules, and thus the MOSFET can be pushed without a booster. Then, two channel driving signals with a phase difference of 90° can be generated through push-pull circuits. To realize step operating of the actuator, the counter module is used to control the driving signal cycle numbers of the driver. If the driver is set at the running mode, a continuous driving signal can be generated. If the driver is set at the stepping mode and the driving wave number is set by a manual encoder, a discontinuous driving signal can be generated as shown in Fig. 5. In this paper, the driving period is set to be 60 ms.

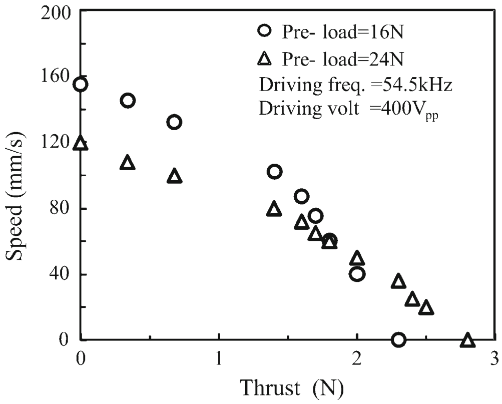


Fig. 6 Mechanical characteristics of the actuator

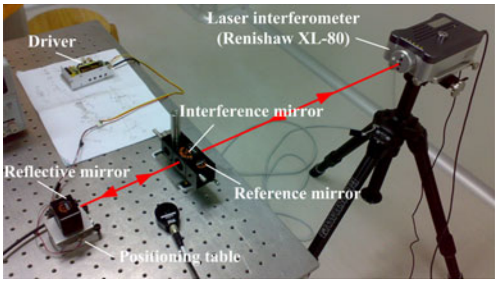


Fig. 7 Measurement setup

3.2 Speed and thrust

In the running mode, the mechanical characteristics of the stage are measured and the results are shown in Fig. 6. The mass of the travelling table plus the mass of the reflective mirror is about 150 g. Under the driving voltage of 400V$_{pp}$, driving frequency of 54.5 kHz, and pre-load of 16 N, the maximum thrust and no-load speed of the stage are 2.3 N and 159 mm/s, respectively. The thrust-weight ratio is up to 12.7, and the maximum efficiency is 7 %. With the pre-load of 24 N, the maximum thrust and the no-load speed of the stage are 2.8 N and 120 mm/s, respectively. The thrust-weight ratio is up to 15.6 and the maximum efficiency is 9 %. Obviously, the no load speed and the thrust of the actuator have an opposite change trend with increasing pre-load.

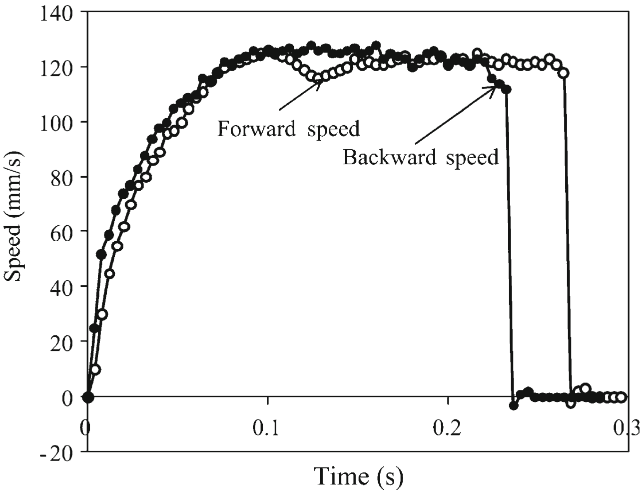


Fig. 8 Characteristics of speed (open-loop)

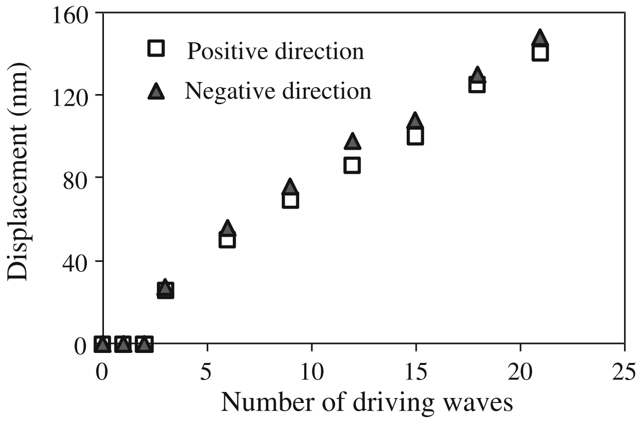


Fig. 9 Resolutions with different driving wave numbers

3.3 Speed responses and stepping resolution

Figure 7 shows the photograph of the experiment setup. A laser interferometer (Renishaw XL-80) with linear measurement accuracy of ±0.5 ppm is used to investigate the dynamic characteristics of the stage. The experiment was carried out in the clean room with grade of 10^5 and vibration isolation has been effectively done. Figure 8 shows the curve of the stage in open-loop speed responses. The no-load speeds of the stage in bi-direction are all 120 mm/s, the start-up time is about 80 ms, and the shutdown time is only 10 ms. Furthermore, the speed characteristics about each direction had a little difference due to the driving source, mounting error, etc.

For precise positioning, stepping operating of the actuator is used. By controlling the driving signal cycle numbers of the driving period, different resolutions (range from 26 nm to 220 nm) can be obtained as shown in Fig. 9. It can be seen that there was no displacement until the driving signal cycle numbers reached three. The reason may be the stator of the motor need a response time due to the damping of the stator. At the same time, there need sufficient driving energy to overcome the static friction of the contact interface of motor. Figure 10 shows the stepping curve of the stage in open-loop stepping operation. Figures 10(a) and (b) present the stepping curve of the stage when the driving wave number is three. Driven by a signal train of 54 μs at the driving period of 60 ms, a finest resolution in the positive direction of 26 nm (shown in Fig. 10(a)) and a finest resolution in the negative direction of 27.5 nm (shown in Fig. 10(b)) are achieved. Obviously, there are different paces in the forward and backward directions. The reason is that there is a slight difference in speed of the stage in both

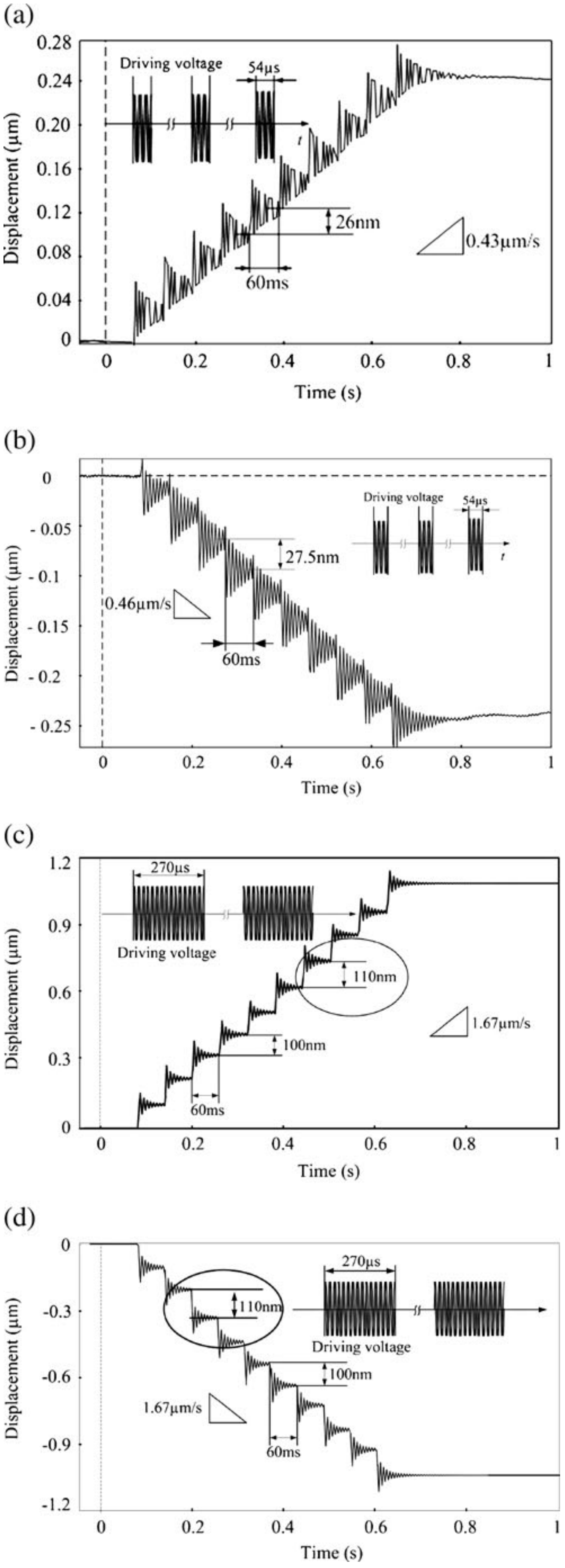


Fig. 10 Stepping curve of the actuator: (**a**) 3 driving waves driving in ▶ positive direction, (**b**) 3 driving waves driving in negative direction, (**c**) 15 driving waves driving in positive direction, and (**d**) 15 driving waves driving in negative direction

directions. Figures 10(c)–(d) show the displacement-time curve of the stage when the driving wave number is 15, where the finest resolutions in both directions are 100 nm. However, it can be seen from Fig. 10(c)–(d) that there is a different step size (110 nm) at the same place in both directions. The reason might be the surface quality of the friction interface between the actuator and the friction plate bonded on the travelling table of the stage.

3.4 Settling characteristics

The actuator can be well servo-controlled. Investigation is performed using the experimental setup shown in Fig. 7 to assess its positioning performance, and the PID control algorithms are adopted. The controller is implemented using a computer. The positioning accuracy is measured by the linear encoder with a resolution of 1 μm. A motion controller is used for the computer-actuator interface. The moving part of the stage is 100 g. The motion of the stage is shown in Fig. 11, which shows the observed position and velocity.

For a traveling distance of 10 mm, the stage motion is successfully controlled; the precise positioning of 1 μm is carried out within 330 ms. Under the control condition of continuous motion mode, The speed of the motor is adjusted by adjusting the driving frequency of the motor and thus the speed is controlled under the condition of <110 mm/s based on the motion position of the stage from 0 to 120 ms. At the position of 9.996 mm, the continuous motion mode is turned off and the stage is settled using the stepping motion mode. Under the stepping motion mode, the stepping size of 1 μm is achieved.

4 Discussion and conclusions

In the view of the shape of the actuator developed in this contribution, there are some similarities with the U-164 PILine piezo linear drive developed by Physik Instrumente Company (http://www.physikinstrumente.com/en/products/prdetail.php?sortnr=1000210.2011-10-6). However, there is much difference. First, the operating principle is different: the operating principle of the actuator developed by PI company is based on asymmetric resonant excitation in the piezoceramic plate in an E(3, 1) mode; the actuator developed in this paper uses L1B2 modes as operating modes. Second, the actuator produced by PI Company is made of piezoceramic plate, which can make the actuator simple and have a higher stiffness. The actuator developed in this paper, however, is a composite piezoelectric actuator, which consists of a metal thin plate and two PZTs. The metal thin plate of the actuator can be actuated by PZTs bonded on it and the amplitude of PZTs can be amplified. In Ref (http://www.physikinstrumente.com/en/products/prdetail.php?sortnr=1000210.2011-10-6), it can be learned that the maximum push-/pull force and maximum velocity of the U-164 PILine piezo linear drive are 4 N and 500 mm/s, respectively. Clearly, compared with the actuator developed by PI Company, the performance of the actuator developed in this paper is not superior. However, the manufacture technology need for the piezoceramic plate used in PI actuator is really high. In some countries, there is no well-equipped technical level to manufacture the piezoceramic plate like PI products. The composite piezoelectric structure can not only decrease the processing requirements but also lower the cost of the actuator. Therefore, the composite piezoelectric actuator remains an effective structure to directly achieve the function of transferring linear motion. At the same time, there are also some similarity between the actuator developed in this paper and the 'shaking beam' actuator described in Ref. [13]. However, there are many differences between them. The major difference is the operating mode of the actuator. The novelty of the actuator developed in the paper is the isosceles triangular structure part of the actuator, which can convert the displacement, while the actuator is operated in the first longitudinal mode, from tangential direction into the normal direction and the displacement is amplified. An effective elliptical motion track can be realized using only two PZTs by the isosceles triangular structure part of the actuator. The detail operating principle can refer to Ref. [24].

In conclusion, a long-range positioning stage driven by a new type piezoelectric linear actuator has been fabricated, and the motion characteristics of the stage are experimentally characterized. Results show that the motion characteristics of the stage are beneficial in some applications that need precision positioning. The step size can be adjusted with the time span of driving pulsed train. The minimum step size is repeatable with a deviation of 26 nm. For a traveling distance of 10 mm, the stage motion is controlled to the target position plus or minus <1 μm within 330 ms. In this paper, the developed stage can realize the nanoscale

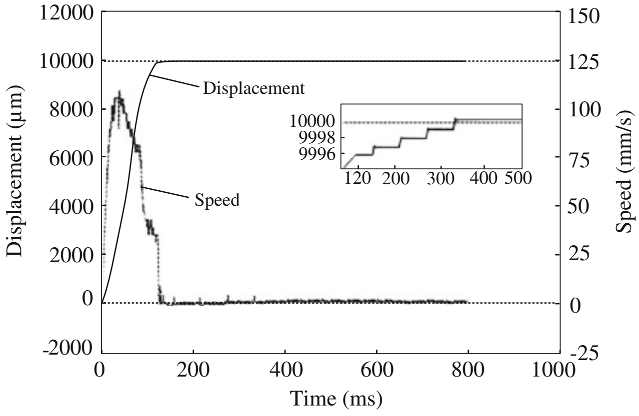


Fig. 11 10 mm travel motion of the stage

resolution. Therefore, the future work is to use the higher resolution linear encoder to meet the needs of higher positioning accuracy.

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