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A novel piezo-driven linear-rotary inchworm actuator

Xiantao Sun [a], Weihai Chen [a], Jianbin Zhang [b,*], Rui Zhou [a], Wenjie Chen [c]

[a] School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
[b] School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China
[c] Mechatronics Group, Singapore Institute of Manufacturing Technology, Singapore 638075, Singapore

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ABSTRACT

This paper presents a novel piezo-driven linear-rotary inchworm actuator with a large motion range and high resolution. Such an actuator will be indispensable in precision positioning. The proposed actuator consists of four flexure modules driven by four piezoelectric actuators, namely, two clamping modules to alternately hold the actuator shaft, one linear driving module and one rotary driving module to provide the driving force and torque, respectively. Its mechanical performance is analyzed in detail and the working principle is also described. A prototype of the linear-rotary actuator is fabricated, with which a series of experiments are carried out. The experimental results show that the actuator can achieve high resolution of 0.049 μm and 10.3 μrad, the maximum velocities of 1450 μm/s and 34,270 μrad/s, and the maximum output force of 11.8 N and maximum output torque of 73.5 N mm for the linear and rotary motions, respectively.

1. Introduction

With the technological developments, precision positioning proves to be a key technique and plays a crucial role in the science and engineering applications, such as scanning probe microscopy, micro/nano surgery, biomedicine, and nanoimprint lithography, etc. [1–5]. Among these applications, the requirements for the motion range and resolution of positioning systems are usually several millimeters and several nanometers, respectively. The factors affecting these characteristics mainly include the actuators, mechanical structures, measurement techniques, and control methods of positioning systems [2,6,7]. Compared with other direct actuators, such as electromagnetic, electrostatic, and shape memory alloy actuators, the piezoelectric actuator (PEA) is an ideal choice as the actuation source due to its merits of compact size, infinite resolution and rapid response. However, the output displacement of the PEA is very small and at most 0.1% of its longitudinal length. Normally, displacement amplification mechanisms are utilized to enlarge the output displacement of the PEA, but the motion range is still limited [8–12]. Moreover, the increased output displacement is at the cost of the decreased output force. This situation leads to the development of some novel piezo-driven actuation techniques, namely, ultrasonic type, inertial type, impact type, and inchworm type, which can overcome the above difficulties [13–17].

Recently, much attention has been focused on the piezo-driven inchworm actuator for various applications, since other piezo-driven actuators usually have smaller driving forces although they possess simpler structures. The piezo-driven inchworm actuator is a bionic actuator with advantages of good controllability, large output force, and large motion range by incrementally summing the small displacement generated by the PEA. This kind of actuator usually includes two clamping sections and one extending section and thus at least three PEAs are required to drive the three sections. For example, Li et al. presented a piezoelectric linear inchworm actuator with three annular PEAs for the shape and vibration control of adaptive truss structures [18]. Zhang and Zhu developed a high-stiffness linear piezomotor with nanometer resolution for precision machine tool applications [19]. Li et al. described a piezo-driven rotary inchworm actuator, which utilized nine PEAs to realize a large rotary range with high accuracy [20]. Zhao et al. designed an inchworm type piezo-driven rotary actuator with the changeable clamping radius [21]. Its rotary velocity can be adjusted not only by the amplitude and frequency of the driving voltage but also by the changeable clamping radius.

However, the existing techniques in the design of piezo-driven inchworm actuators mainly concentrate on the one-degree-of-freedom (one-DOF) actuator [13,16,18–21], i.e., linear or rotary actuator, which is the most widely used actuator in precision positioning. So far, researches on multi-DOF piezo-driven inchworm actuators are rare. Although a few multi-DOF piezo-driven mechanisms based on the inchworm motion are developed [22–24], they seem more like mobile robots than like actuators since their

* Corresponding author. Tel.: +86 10 82315560; fax: +86 10 82315920.
E-mail address: jbzhangbuaa@126.com (J. Zhang).

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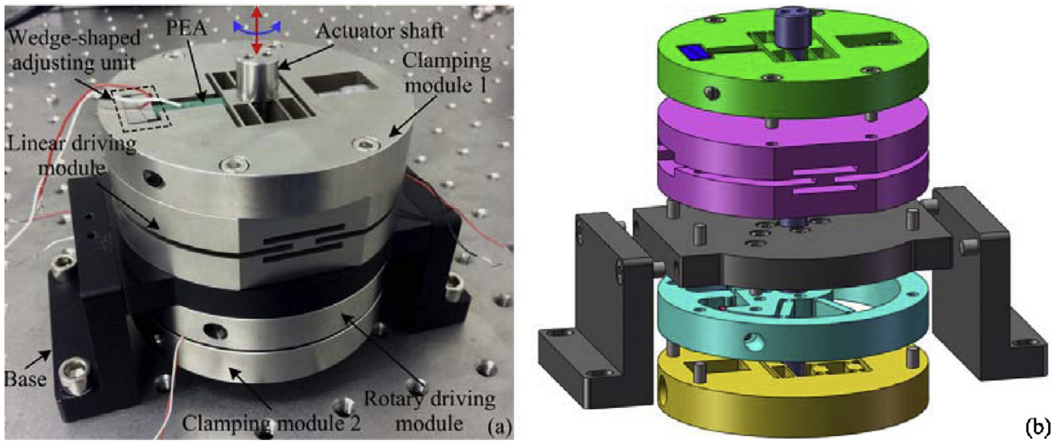

Fig. 1. (a) Prototype and (b) exploded diagram of CAD model of the piezo-driven linear-rotary inchworm actuator.

output ends are not unique for different DOF motions. The structural mode of the linear-rotary actuator with the identical motion axis for translation and rotation is the optimal configuration manner in the two-DOF actuators for precision positioning. The objective of this paper is to develop a novel piezo-driven linear-rotary inchworm actuator with a large motion range, high resolution, and large output force and torque.

In the remainder of this paper, the detailed structural analysis is conducted in Section 2. Then, the motion principle of the linear-rotary actuator is described in Section 3. Finite element analysis is performed to evaluate the static and dynamic performance of the actuator in Section 4. A prototype of the proposed actuator is constructed as shown in Section 5, followed by the experimental tests and discussions. Finally, this paper is concluded in Section 6.

2. Structural analysis

For the linear-rotary actuator, the decoupled characteristic is very important, that is to say that the linear and rotary motions should be controlled independently. Since a one-DOF inchworm actuator usually includes three PEAs, at least six PEAs are required to design a decoupled linear-rotary inchworm actuator. To reduce the number of PEAs and meanwhile reduce the required drive electronics, a tradeoff is made that only one of the linear and rotary motions is implemented at a time. It is known that the two-DOF linear-rotary motion can be considered as the serial combination of the one-DOF linear and rotary motions. Thus, this tradeoff does not affect the motion performance of the linear-rotary actuator in most cases.

Fig. 1 shows the prototype and exploded diagram of CAD model of the piezo-driven linear-rotary inchworm actuator. It can be seen that the actuator mainly consists of an actuator shaft and a five-layer structure which is assembled with a clamping module 1, a linear driving module, a stationary base, a rotary driving module, and a clamping module 2 from top to bottom. Two clamping modules are placed at the two sides of the driving modules, respectively. Moreover, there is one PEA in each module to perform the clamping or driving function. This compact configuration makes it possible to implement the linear and rotary inchworm motions sharing two clamping modules at the action of their respective driving modules by only using four PEAs. It is noted that the base is located in the middle of other four modules. However, it does not affect the motion performance of the actuator even if the base is located at the bottom of them. For the second layout, four modules are connected in series, while for the first layout, only two modules are connected in series and meanwhile the two driving modules are secured to the base. There is no doubt that the first layout can improve the stability of the actuator.

Two complementary clamping structures are adopted in the two clamping modules, where the module 1 holds the actuator shaft under a high voltage and releases it under a low voltage while the situation is exactly opposite for the module 2. This means that the actuator possesses the power-off hold characteristic, i.e., the output shaft can be still held firmly by the clamping module 2 even if the power is off. Moreover, all components of the actuator should be assembled together carefully to guarantee the working precision.

2.1. The clamping modules

As shown in Fig. 2, to achieve a large clamping force and avoid the decreased output force induced by displacement amplification mechanisms, the direct motion mode of the PEA is adopted in the clamping module 1. The clamping block with circular notch is suspended by four flexure beams which form a double-parallelogram flexure mechanism. The initial clearances between the two clamping blocks and the actuator shaft can be finely adjusted by a wedge-shaped adjusting unit with displacement reduction function and a micrometer head, respectively. Apart from the clearance adjusting, the wedge-shaped adjusting unit can also preload the PEA. When the PEA gets charged, the left clamping block is pushed to hold the actuator shaft firmly.

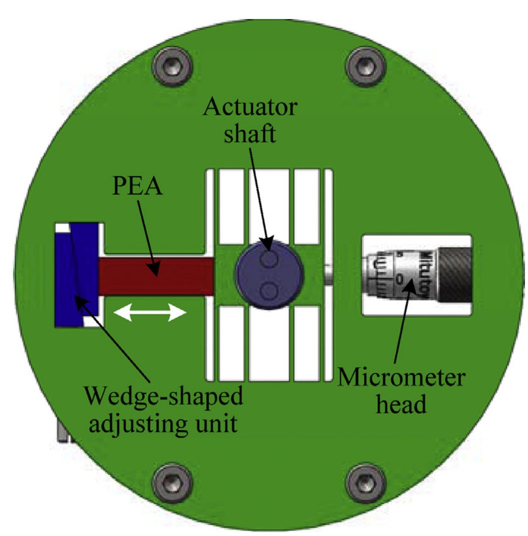

Fig. 2. Clamping module 1.