An X-Y-Theta actuator using piezoelectric elements and electropermanent magnets

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Abstract
Microactuators with multi-degree-of-freedom, which offer significant advantages for precision engineering, are essential for industrial applications. In this study, we propose a microactuator capable of moving in the x, y, and theta (θ) directions. The actuator comprises three piezoelectric elements (piezos) and three electropermanent magnets (EPMs). The multi-layered piezos are arranged into an equilateral triangle, allowing for extension and contraction along the sides. The EPMs are attached to the vertices of the triangle. The EPM consists of two types of magnetic material: a hard magnetic material that exhibits permanent magnetisation and a soft magnetic material that can be temporarily magnetized or demagnetized through the application of an electric current pulse. The external magnetic field of the EPM can be activated and deactivated by a short current pulse, enabling the actuation of adhesion forces with minimal energy expenditure. The operational principle of the proposed actuator is based on an inchworm mechanism where two EPMs are energized while a third deactivated EPM enables minute displacement through piezo deformation. The movement of three EPMs, sequentially switched off, is achieved by the deformation of the piezos. To achieve long-distance movement, the sequence of small displacements of EPMs is repeated. This paper provides a detailed description of the proposed actuator. The smallest displacement of the proposed actuator per control cycle is approximately 5.33 μm in linear displacement and 0.31 mrad in angular displacement while its largest displacement is 0.12 mm in linear displacement and 1.86 mrad in rotational displacement.

Piezoelectric element, electropermanent magnet, EPM, inchworm, actuator

1. Main section heading

The downsizing of production equipment is attracting attention as products become more compact. The advantages of downsizing production equipment include space savings and energy savings, as smaller parts require less operational energy [1]. Piezoelectric elements (piezos), capable of generating minute displacements, are widely applied in compact systems. Various actuators using piezos have been introduced [2]. A mechanism operated by controlling the expansion and contraction of the piezos and the frictional force [3] and a mechanism moved by controlling the expansion and contraction speed of the piezo [4] are developed. An inchworm mechanism that uses piezos and electromagnets is also developed [5]. The electromagnets however consume a large amount of energy although they are small in size. This paper investigates the linear and rotational motion of an X-Y-Theta actuator that employs an electropermanent magnet (EPM) as the position holding mechanism, in conjunction with piezos. The utilization of EPMs with short current pulses has the potential to reduce the power consumption of the X-Y-Theta actuator.

2. An X-Y-Theta actuator

Figure 1 shows a schematic diagram of an EPM composed of a neodymium magnet and an alnico magnet connected in parallel. The neodymium magnet is high coercivity magnetic material and the alnico magnet is low coercivity material. The external magnetic field from the EPM can be turned on and off by reversing the magnetization of the alnico magnets with short current pulses. The magnetization of the neodymium and alnico magnets are aligned to generate an adhesion force as shown in Figure 1a. By reversing the direction of the magnetization of the alnico magnets by a current pulse, the external magnetic field disappears and no adhesive force is generated as shown in Figure 1b. Therefore, the EPM can switch on and off by a short current pulse and a small electric power.

Figure 2 shows a photograph of an X-Y-Theta actuator using three piezos and three EPMs. The piezos are 20 mm long and deform 16 μm by 150 V_{DC}. The displacement amplification mechanism magnifies the deformation of the piezos by a factor of 6.67. The EPM consists of a 15 mm long neodymium magnet and an alnico magnet. The alnico magnet is wound by a 300-turn coil. The electromagnetic force generated by an on-state EPM is 45 N which is measured by a force gauge. The friction force of an off-state EPM is 0 N and that of an on-state is 45 N. Two of three EPMs are on-state. The piezos move the position of the EPM in

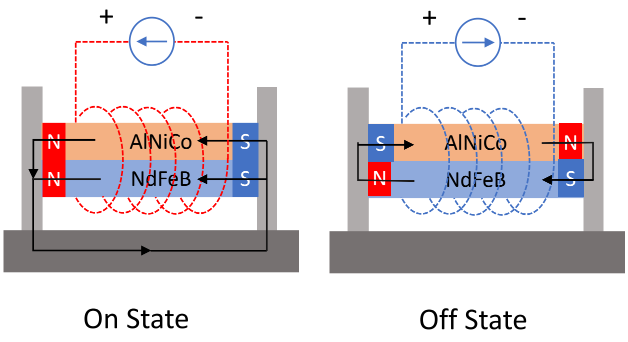

Figure 1. Electropermanent magnets

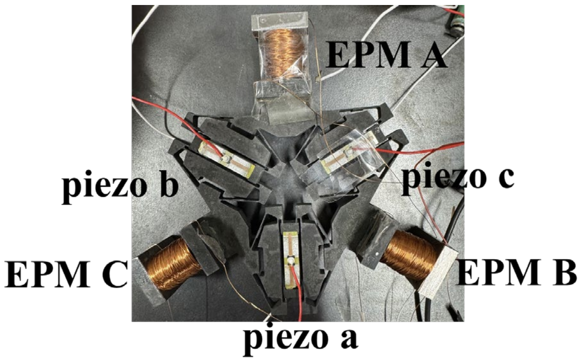

Figure 2. X-Y-Theta actuator using piezoelectric elements and electropermanent magnets

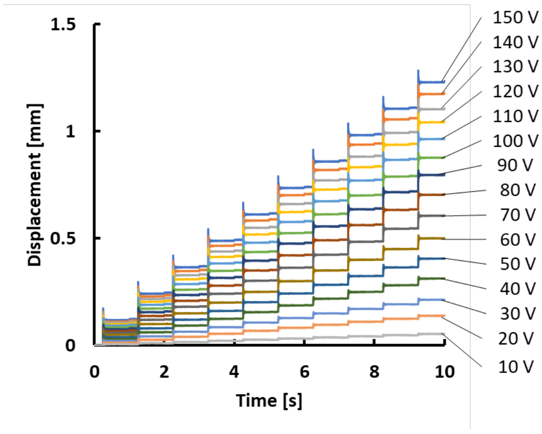

Figure 3. Displacement of linear motion

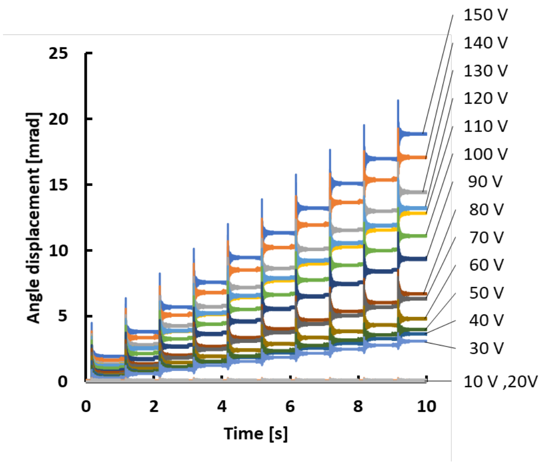

Figure 4. Angle displacement of rotational motion

the off-stage. The situation of EPM changes every 0.333 s while the pulse width of EPM is 5 ms.

A 6 A and 5 ms current pulse changes the magnetization of the EPMs and an off-state EPM are moved by the piezos. The intervals of the current pulse are 0.667 s. Since three EPMs move sequentially, three intervals consist one control cycle. The linear displacement of the actuator is achieved by the following sequence. The extensions of piezo b and piezo c moves off-state EPM A while EPM B and EPM C are on-state, the contraction of piezo c moves off-state EPM B while EPM C and EPM A are on-state, and the contraction of piezo b moves off-state EPM C while EPM A and EPM B are on-state. The rotational displacement of the actuator in the clockwise direction is achieved by the following sequence. The extension of piezo b and contraction of piezo c moves EPM A while EPM B and EPM C are on-state, the contraction of piezo b and extension of piezo a moves EPM C while EPM A and EPM B are on-state, and the contraction of piezo a and extension of piezo c moves EPM B while EPM C and EPM A are on-state.

3. Experimental method

The signals described in the previous section are applied to each component of the X-Y-theta actuator to move in the linear displacement and to rotate in the clockwise displacement. The voltage input to the piezo is changed from 10 V to 150 V every 10 V, and the linear and rotational displacement are measured. The linear displacement is defined as the position change of EPM A which is measured by commercially available displacement meter. The angular displacement is calculated by the ratio of the tangential displacement of EPM B, which is measured by the displacement meter, and the radius of the X-Y-Theta actuator, which equals 55 mm. One control cycle equals 1 s.

4. Results and discussion

Figure 3 shows the results of the linear operation. The displacement of the linear motion is 0.12 mm per cycle when 150 V is applied to the piezo, and 5.33 µm per cycle when 10 V is applied. The step displacement of one control cycle is approximately proportional to the voltage applied to the piezo. The displacement magnification mechanism enables the actuator to achieve the incremental displacement.

Figure 4 shows the results of the rotational operation. The angler displacement per cycle for rotational motion is 1.86 mrad when 150 V is applied, and 0.31 mrad when 10 V is applied. The step angular displacement of one control cycle is generally proportional to the voltage applied to the piezos. However, the step angular displacements achieved by voltages smaller than 60 V fluctuate. Some friction forces caused by small input voltages affect the angular displacement.

5. Conclusion

This paper described an X-Y-Theta actuator using piezoelectric elements and electropermanent magnets, which were responsible for the actuator's position retention mechanism and switches between position retention and release with a short pulse current. Since the amount of extension of the piezo was equal to the deformation of the piezo actuator, the displacement of the actuator was proportional to the voltage applied to the piezo. A maximum displacement of 0.12 mm per cycle was achieved for linear motion, and 1.86 mrad per cycle for rotational motion.

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