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Performance of an X-Y-Theta actuator using piezoelectric elements and electropermanent magnets

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Abstract

Microactuators with multiple degrees of freedom offer significant advantages in precision engineering, and are essential in various industrial applications. We proposed an X, Y, and theta (θ) microactuator which consists of three multilayer piezoelectric elements (piezos) and three electropermanent magnets (EPMs). The piezos are arranged to form an equilateral triangle, allowing extension and contraction along its sides, while the EPMs are positioned at the triangle's vertices. Each EPM can switch an electromagnetic force via a short current pulse. The principle of the X-Y-Theta actuator is based on an inchworm mechanism. While two EPMs remain activated, the third—temporarily deactivated—allows minute displacement through deformation of the piezos. Sequential deactivation of the EPMs results and cyclic deformation of the piezos enables long-range motion through repeated incremental steps. This paper presents a preliminary performance of the X-Y-Theta actuator utilizing EPMs and piezos. The principle of the actuator is described followd by experimental results, which demonstrate a linear step displacement of 15 µm and a rotational displacement of 1.3 mrad. These performance metrics can be further improved by applying smaller deformation steps to the piezos.

Piezoelectric element, electropermanent magnet, EPM, inchworm, actuator

1. Introduction

The downsizing of production equipment has gained attention as products become compact. Miniaturization offers advantages such as improved space efficiency and reduced energy consumption. Piezoelectric elements (piezos), which can generate minute displacements, are widely used in compact systems, and various piezo-based actuators have been developed [1]. Examples include mechanisms driven by controlling piezo extension and contraction combined with frictional forces [2]. An inchworm mechanism incorporating piezos and electromagnets has been introduced [3]. However, electromagnets consume substantial energy.

This study shows the preliminary performance of the linear and rotational motion of an X-Y-Theta actuator that uses three electropermanent magnets (EPMs) [4] as a position-holding mechanism in conjunction with three piezos. The use of EPMs, which require short current pulses to switch the electromagnetic force, has the potential to reduce the power consumption of the X-Y-Theta actuator.

2. Electropermanent magnet and X-Y-Theta actuator

Figure 1 shows the schematic diagram of an EPM and an X-Y-Theta actuator. The EPM composed of a neodymium magnet and an alnico magnet arranged in parallel as shown in Figure 1(a). The neodymium magnet is a high-coercivity material, while the alnico magnet exhibits low coercivity. A coil is wound around the alnico magnet. The external magnetic field generated by the EPM can be switched on and off by reversing the magnetization of the alnico magnet using short current pulses. When the magnetizations of the neodymium and alnico magnets are aligned, a magnetic attractive force is produced. Reversing the magnetization of the alnico magnet eliminates the external magnetic field, resulting in no attractive force. This mechanism enables the EPM to switch between on- and of-f states using short current pulses. Figure 1(b) shows the schematic diagram of a delta-type X-Y-Theta actuator. At any moment, two out of three EPMs are on-state, and the other is off-state. The off-state EPM is displaced by the extension and contraction of the piezos connetected.

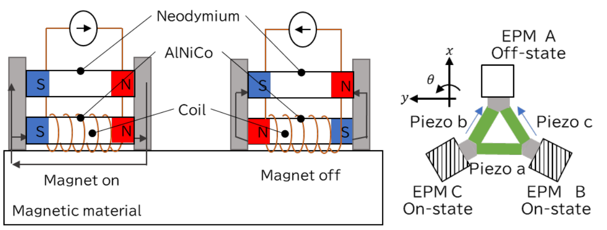

Figure 1. Schematic diagram of electropermanent magnet and X-Y-Theta actuator

Linear displacement in the x-direction is achieved by table 1. First, the on/off states of the EPMs are set by current pulses. Then, the off-state EPM is displaced by the extension and contraction of the piezos. This two-state sequence is repeated. Counter clockwise rotational displacement in the θ-direction is achieved by table 2. In all states, the on/off states of the EPMs are set by current pulses prior to the extension and contraction of the piezos, causing the EPM in the off-state to be displaced. This three-state sequence is three-state sequence is repeated.

Table 1. sequence of linear displacement in x direction

State	EPM			piezo		
	A	B	C	a	b	C
1	off	on	on	contract	extend	Extend
2	on	off	off	contract	contract	Contract

Table 2. Sequence of counter clockwise rotational displacement

state	EPM			piezo		
	A	B	C	A	b	C
1	off	on	on	contract	contract	Extend
2	on	on	off	contract	extend	Contract
3	on	off	on	extend	contract	Contract

3. Experimental setup

Figure 2 shows the photographs of a side view of an EPM and a top view of an X–Y–Theta actuator incorporating three piezos and three EPMs. In Figure 2(a), the EPM consists of a 15 mm long and 8 mm diameter alnico magnet and neodymium magnet, with the alnico magnet wound by a 300-turn coil. The residual magnetic flux density of the alnico magnet and the neodymium magnet is 1.20 T and 1.17 T – 1.23 T, respectively. The friction force generated by the on-state EPM is 50 N, while the friction force of the off-state EPM is 0 N. In Figure 2(b), the piezos are 20 mm long and exhibit a deformation of 17 µm under an applied voltage of 150 V DC. Flexure hingies are used at both ends of the piezos.

The EPM state is updated prior to extension or contraction of the piezos. A positive pulse switches the EPM to the on-state, while a negative pulse switches it to the off-state. A current pulse of 6 A and 5 ms is applied to reverse the magnetization of the alnico magnet. An off-state EPM is displaced by the deformation of the piezos.

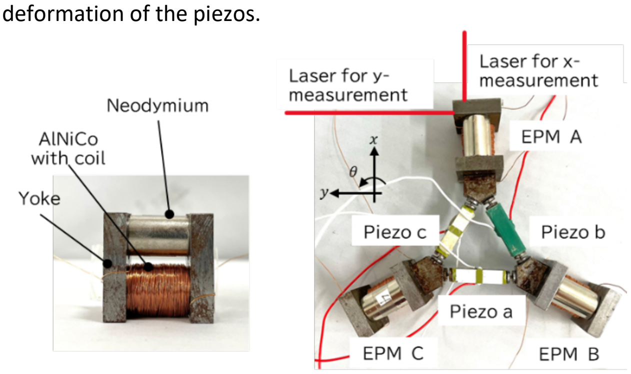

Figure 2. photographs of EPM and X-Y-Theta actuator

The control signals are applied to each component of the X–Y–Theta actuator to achieve both linear and rotational displacement. The input voltage to the piezo is 150 V or 0 V, and the resulting linear and rotational displacements are measured. The displacement is measured as shown in Figure 2(b). The linear displacement in the x-direction is defined as the position change of EPM A, which is measured using a commercially available displacement sensor. The rotational displacement in the theta-direction is calculated from the ratio of the tangential (y) displacement of EPM A, which is also measured by the displacement sensor, to the radius of the actuator, which is 50 mm. One full control cycle corresponds to a duration of 1 s.

4. Results and discussion

Figure 3 shows the results of the linear operation. The linear displacement, the voltage applied to piezo b and piezo c, and the current pulse applied to EPM B are shown. The linear displacement is synchronized with the extension of the piezo b and piezo c, and the displacement of the off-state EPM A reaches approximately 20 µm. However, a reverse displacement of approximately 5 µm is observed when the state of EPM B switches from the off-state to the on-state, reducing the net displacement per cycle. Consequently, the resulting displacement per control cycle is approximately 15 µm.

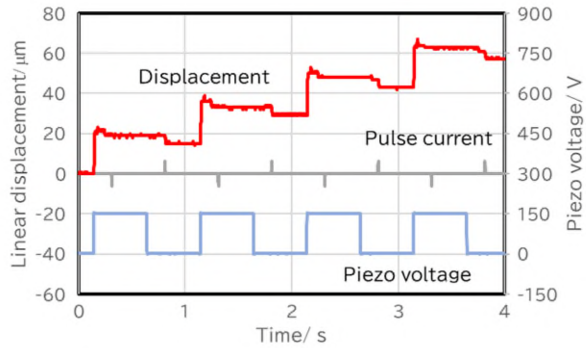

Figure 3. Linear displacement, pulse current, and piezo voltage

Figure 4 shows the results of the rotational operation. The rotational displacement, the voltage applied to piezo C, and the current pulse applied to EPM A are shown. The rotational displacement is synchronized with the extension of the piezo c, and the rotational displacement per cycle of the off-state EPM A reaches 1.3 mrad. In contrast to the linear operation, a reverse rotational displacement does not occur.

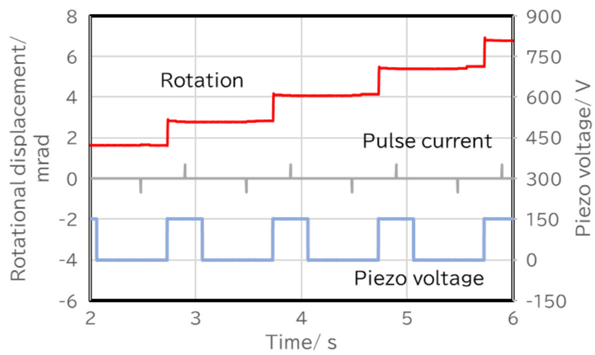

Figure 4. Rotational displacement, pulse current, and piezo voltage

5. Conclusion

This study presented an X–Y–Theta actuator using piezoelectric elements and electropermanent magnets, which serve as the position-holding mechanism and enable switching between the on-state and off-states using short current pulses. Experimental results demonstrated a linear displacement of 15 µm per cycle and a rotational displacement of 1.3 mrad per cycle. These performance metrics can be further improved by applying closed-loop control of the X-Y-Theta actuator. By incorporating high-precision feedback sensors, it will be possible to compensate for environmental disturbances. This approach is expected to improve positioning accuracy, enabling the actuator to support applications requiring nanometer-level control.

References

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